

# Centimetre-wave continuum radiation from the $\rho$ Ophiuchi molecular cloud

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## ABSTRACT

The  $\rho$  Oph molecular cloud is undergoing intermediate-mass star formation. Ultraviolet radiation from its hottest young stars heats and dissociates exposed layers, but does not ionize hydrogen. Only faint radiation from the Rayleigh-Jeans tail of  $\sim 10$ – $100$  K dust is expected at wavelengths longwards of  $\sim 3$  mm. Yet cosmic background imager (CBI) observations reveal that the  $\rho$  Oph W photodissociation region is surprisingly bright at centimetre wavelengths. We searched for interpretations consistent with the *Wilkinson Microwave Anisotropy Probe* radio spectrum, new *Infrared Space Observatory*-Long Wavelength Spectrograph (LWS) parallel mode images and archival *Spitzer* data. Dust-related emission mechanisms at 1 cm, as proposed by Draine & Lazarian, are a possibility. But a magnetic enhancement of the grain opacity at 1 cm is inconsistent with the morphology of the dust column maps  $N_d$  and the lack of detected polarization. Spinning dust, or electric-dipole radiation from spinning very small grains (VSGs), comfortably explains the radio spectrum, although not the conspicuous absence from the CBI data of the infrared circumstellar nebulae around the B-type stars S1 and SR3. Allowing for VSG depletion can marginally reconcile spinning dust with the data. As an alternative interpretation, we consider the continuum from residual charges in  $\rho$  Oph W, where most of carbon should be photoionized by the close binary HD 147889 (B2IV, B3IV). Electron densities of  $\sim 10^2$  cm $^{-3}$ , or H-nucleus densities  $n_H > 10^6$  cm $^{-3}$ , are required to interpret  $\rho$  Oph W as the C II Strömgren sphere of HD 147889. However, the observed steep and positive low-frequency spectral index would then imply optically thick emission from an hitherto unobserved ensemble of dense clumps or sheets with a filling factor of  $\sim 10^{-4}$  and  $n_H \sim 10^7$  cm $^{-3}$ .

**Key words:** radiation mechanisms: general – ISM: clouds – radio continuum: general – radio continuum: ISM – submillimetre.

## 1 INTRODUCTION

The subtraction of Galactic foregrounds in experiments designed to map the cosmic microwave background requires the examination of the emission mechanisms at work in the interstellar medium (ISM). An anomalous component of continuum emission was discovered

in the direction of Galactic cirrus clouds (Leitch et al. 1997), so defined by their H I 21 cm and far-infrared (far-IR) contours (e.g. Boulanger & Perault 1988). The LDN 1622 dark cloud (Lynds Dark Nebula, Lynds 1962) was found to be bright at cm-wavelengths, where no known emission mechanisms were expected (Finkbeiner et al. 2002; Finkbeiner 2004; Casassus et al. 2006). At the time of writing, LDN 1622 is the only dark cloud known to radiate at cm-wavelengths.

What is the nature of the cm-wave emitters? Do the dark clouds and the cirrus clouds radiate by the same emission mechanisms?

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Draine & Lazarian (1998a,b) proposed electric-dipole radiation from polarized very small dust grains (VSGs) spinning at GHz frequencies or spinning dust. Draine & Lazarian (1999) also suggested that ‘magnetic dust’, or magnetic dipole emission due to thermal fluctuations in the magnetization of ferromagnetic grains, could produce detectable cm-wave emission. However, a finite charge density exists in atomic and molecular clouds; a small part of the neutral material is ionized by exposure to pervasive cosmic rays or soft-ultraviolet (soft-UV) photons (e.g. Tielens 2005). As an alternative to spinning dust, could the residual charges radiate at the observed levels?

Prototypical and well-studied local clouds can give information on the environments giving rise to cm-wave radiation. The  $\rho$  Oph molecular cloud (e.g. Encrenaz 1974; Young et al. 2006), at a distance  $D = 135 \pm 15$  pc (parallax distance to HD 147889, Habart et al. 2003), lies in the Gould Belt of the closest molecular complexes.  $\rho$  Oph is an undergoing intermediate-mass star formation – the most massive of its young stars is HD 147889, which we show here to be a close pre-main-sequence B2, B3 binary, not hot enough to form a conspicuous region of ionized hydrogen (H II region). A description of the region can be found in fig. 4 of Young et al. (2006).

Here we present the first resolved images at cm-wavelengths of the  $\rho$  Oph main cloud, LDN 1688. We describe our observations in Section 2, as well as auxiliary data in Section 3, including unpublished *Infrared Space Observatory*-LWS (ISO-LWS) parallel mode data. We proceed to summarize the available imaging and spectroscopic data in Section 4. The dust emission from  $\rho$  Oph W and the contribution of spinning or magnetic dust at cm-wavelengths are studied critically in Section 5. We also propose in Section 6 an alternative emission mechanism for the 31 GHz emission based on the C I continuum from a cold plasma. In Section 7, we analyse the non-detection of the radio recombination line system in  $\rho$  Oph W. We discuss our findings in Section 8 in terms of the C II Strömgren spheres around the early-type stars that are interacting with the  $\rho$  Oph cloud, before concluding in Section 9.

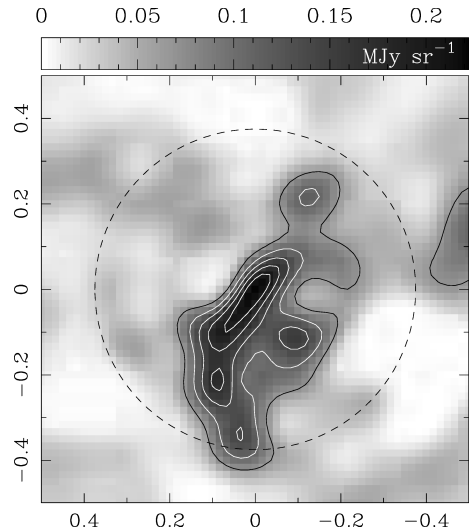
## 2 COSMIC BACKGROUND IMAGER OBSERVATIONS

The 31 GHz image of  $\rho$  Oph that motivates this work is shown in Fig. 1. It was reconstructed from the cosmic background imager (CBI) visibilities using a maximum entropy method (MEM). In this section, we give details on the CBI observations and image reconstruction.

### 2.1 Total intensity

The CBI (Padin et al. 2002) is a planar interferometer array with 13 antennas, each 0.9 m in diameter, mounted on a 6 m tracking platform. The CBI receivers operate in 10 frequency channels covering 26–36 GHz. It is located in Llano de Chajnantor, Atacama, Chile. With a uniform-weight synthesized beam of  $\sim 6$  arcmin and a primary beam of 45.2 arcmin full width at half-maximum (FWHM) at 31 GHz, the CBI is well suited to image clouds  $\sim 20$ –30 arcmin in total extent. The CBI primary beam (CBI PB) encompasses most of LDN 1688.

During three nights of 2004 July and 2005 April, we acquired 31 GHz visibilities in a single pointing on the  $\rho$  Oph W photodissociation region (PDR, Habart et al. 2003), with the CBI in its compact configuration, for a total of  $\sim 12\,000$  s on-source. Baseline length ranged between 100 and  $400\lambda$ , corresponding to spatial scales of



**Figure 1.** MEM model of the CBI 31 GHz visibilities.  $x$ - and  $y$ -axes show offset RA and Dec. from  $\rho$  Oph W (J2000  $16^{\text{h}}25^{\text{m}}57^{\text{s}}$ ,  $-24^{\text{d}}20^{\text{m}}50^{\text{s}}$ ), in degrees of arc. The contour levels are at 0.067, 0.107, 0.140, 0.170 and 0.197, in  $\text{MJy sr}^{-1}$ . The dashed-circle follows the half-maximum level of the CBI PB.

34.4 and 8.6 arcmin, respectively. Cancellation of ground and Moon contamination was obtained by differencing with a leading reference field at the same declination but offset in hour angle by 10 m, the duration of the on-source integration.

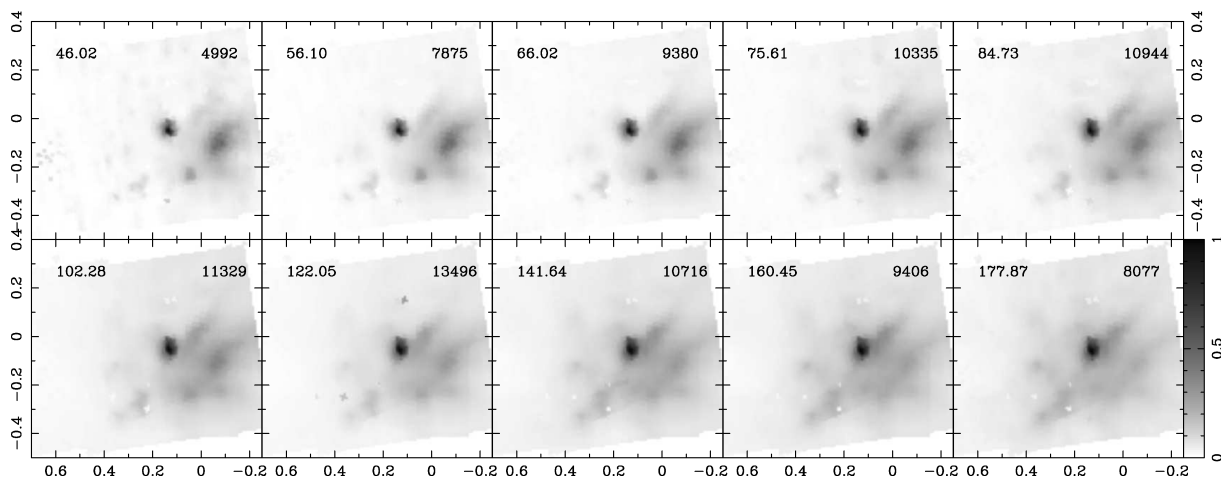
### 2.2 Image reconstruction

We produced the MEM model in Fig. 1 by minimizing the model functional  $L = \chi^2 - \lambda S$ , where the expression for  $\chi^2$  is given by equation (A1) in Casassus et al. (2006), and with  $S = -\sum_i I_i \log(I_i/M_i)$ , where  $\{I_i\}_{i=1}^N$  is the model image and  $M_i$  is an image prior. The sum extends over the number of independent data points, which is  $f = 31\,680$  (two for each of 15 840 complex visibilities). In this case, we chose a regularizing parameter  $\lambda = 200$ , and square model images with  $256^2$  square pixels, each 1 arcmin on a side. The optimization converged in 20 iterations. The image prior was constructed from a combination of the Infrared Array Camera (IRAC) four image at  $8\,\mu\text{m}$  (see Section 3.2) and *Wilkinson Microwave Anisotropy Probe* (WMAP) Ka at 33 GHz (see Section 3.5). More details on image reconstruction are given in Section A.

### 2.3 Polarization

$\rho$  Oph was also observed by the CBI in polarization during four nights in 2004 August, September and October. The details of the polarization calibration and data reduction procedures can be found in Readhead et al. (2004); Cartwright et al. (2005); Dickinson et al. (2006) and Casassus et al. (2007). Data from all nights were combined together. They were mapped with DIFMAP using natural weights and optimal noise weighting. A polarized intensity map was created using AIPS COMB and POLC option to correct for the noise bias. The noise on the Q and U maps is about  $9\,\text{mJy beam}^{-1}$ . The beam is  $9.5 \times 8.3\,\text{arcmin}^2$ .

No obvious polarization signal is visible in the polarized intensity map, and is consistent with an rms noise of  $12\,\text{mJy beam}^{-1}$ . Using the same weighting scheme (same visibilities and synthesized beam), the peak total intensity is  $752\,\text{mJy beam}^{-1}$ .



**Figure 2.** The *ISO*-LWS parallel mode data on  $\rho$  Oph.  $x$ - and  $y$ -axes show offset RA and Dec. from  $\rho$  Oph W, in degrees. The centre wavelength in microns of the LWS channels is indicated on the upper left-hand panel of each image. The intensities in  $\text{MJy sr}^{-1}$  have been scaled by the amount indicated on the upper right-hand panel of each image.

At peak total intensity, the  $1\sigma$  polarization limit is  $12/752 = 1.6$  per cent, or a  $3\sigma$  upper limit of 4.8 per cent. In the weaker regions of  $\rho$  Oph W, where the total intensity drops to typically  $100\text{--}200 \text{ mJy beam}^{-1}$ , the polarization limit increases to  $\sim 12/150 = 8$  per cent, or 24 per cent at  $3\sigma$ .

For the integrated flux density over a 45 arcmin diameter aperture, the polarization limit has to be calculated using a primary-beam corrected map which multiplies up both the signal and noise. This was done, making a noise-corrected polarized intensity map assuming a noise level of  $45 \text{ mJy beam}^{-1}$  (average over the field). The rms in this image is  $57 \text{ mJy beam}^{-1}$ . So, the integrated polarization limit is 1.0 per cent at  $3\sigma$ .

### 3 AUXILIARY DATA

#### 3.1 *ISO* parallel mode data

The *ISO* Long Wavelength Spectrograph parallel mode survey<sup>1</sup> covered most of LDN 1688 in 10 bands ranging from 46 to  $178 \mu\text{m}$ . The full set of *ISO* images is shown in Fig. 2. The broad wavelength coverage of the *ISO* data allows dust mass and extinction estimates (see Section 5.1). Especially relevant to this work is the  $178\text{-}\mu\text{m}$  image, which is used in the discussion of magnetic dust in Section 5.2.

The parallel mode data were obtained when another *ISO* instrument was operating with total sky coverage of about 1 per cent. The processing of parallel data was the same as for the primary mode data. Engineering conversions were applied to obtain the photocurrents. Once the photocurrents were obtained the dark current was removed. The calibration of the detector responsivity relies on a simple ratio between the response to the illuminators found at the time of a particular observation and that used as a reference. Parallel mode maps were produced at 10 detector wavelengths and are generated by combining different rasters. Several data reduction tools were developed in IDL and these form the LWS parallel interactive analysis package that can be found at <http://jackal.bnsc.rl.ac.uk/isouk/lws/software/software.html>.

We have compared the *ISO* data at  $102.26 \mu\text{m}$  with the *IRAS*  $100 \mu\text{m}$  survey (Wheelock et al. 1994). It is noteworthy that the *ISO*  $102.26 \mu\text{m}$  intensities below  $1000 \text{ MJy sr}^{-1}$  are typically 27 per cent higher than *IRAS*  $100 \mu\text{m}$ , 40 per cent higher above  $1000 \text{ MJy sr}^{-1}$ . This is in agreement with the results of Chan (2001). According to the *IRAS* explanatory supplement, the gain and non-linearity of the detectors is a function of source extension, which could be the source of the intensity-dependent discrepancy between *ISO* and *IRAS*.

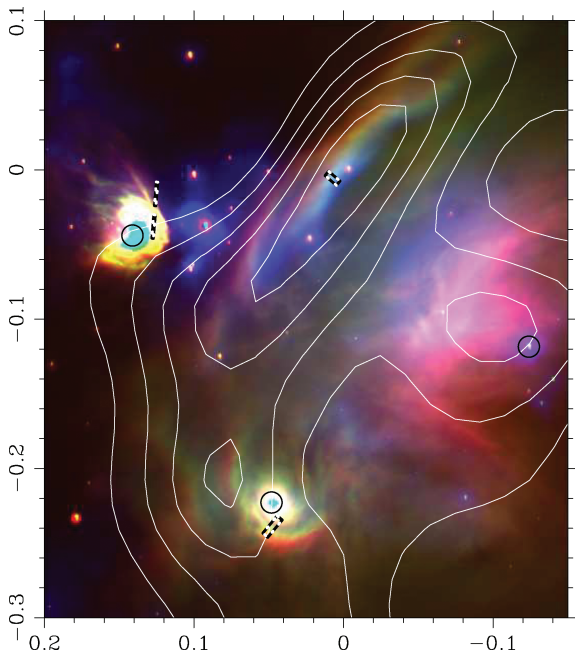
#### 3.2 *Spitzer* archival data

The IRAC data span the range  $3.6\text{--}8 \mu\text{m}$  with four distinct bands (centered at 3.6, 4.5, 5.6 and  $8 \mu\text{m}$ ) and an angular resolution of 2 arcsec. Longer wavelengths, namely 24, 70 and  $160 \mu\text{m}$ , are covered by MIPS data, with angular resolutions of 9, 18 and 40 arcsec, respectively. Both the IRAC and MIPS data considered in this paper come from the *c2d* *Spitzer* Legacy Survey.<sup>2</sup> The MIPS data are described by Padgett et al. (2008), in connection with the young stellar population of  $\rho$  Oph.

Archival *Spitzer* IRS data were obtained for positions near the early-type stars S1, SR3 and a region of the filament. For SR3 and the filament (Berné et al. 2007), the data were taken in spectral mapping mode using the high-resolution [Short-High (SH) and Long-High (LH)] modules of IRS. In this mode, the spectrograph slit is moved before each integration in order to cover the region of interest. The basic calibrated data (BCD) files from the archive were produced using the S15 pipeline by the *Spitzer* Science Centre. The spectral cubes were assembled from the BCD files using the CUBISM software package (Smith et al. 2004). Spectra were extracted from the spectral cubes using an aperture which was covered by both SH and LH modules, as shown in Fig. 3. For S1, the data were taken in low-resolution [Short-Low (SL)] staring mode and were also produced using the S15 pipeline. The original target was a young stellar object (J162630–242258, Barsony et al. 1997) located behind the circumstellar nebula about S1. We performed a full-slit extraction of SL1 with the target in the SL1 slit and also with the target in

<sup>1</sup> [http://www.iso.vilspa.esa.es/manuals/HANDBOOK/lws\\_Hbnode1.html](http://www.iso.vilspa.esa.es/manuals/HANDBOOK/lws_Hbnode1.html)

<sup>2</sup> See the *Spitzer* Science Centre press release, <http://www.spitzer.caltech.edu/Media/releases/ssc2008-03/release.shtml>.



**Figure 3.** Three-colour image of  $\rho$  Oph W: red: MIPS 24  $\mu\text{m}$ ; green: IRAC 4 at 8  $\mu\text{m}$ , dominated by the 7.7  $\mu\text{m}$  PAH band and blue: 2MASS  $K_s$ -band image.  $x$ - and  $y$ -axes show offset RA and Dec. from  $\rho$  Oph W, in degrees. The dashed black and white boxes indicate the extraction apertures for the *Spitzer* IRS spectroscopy discussed in Section 5.3 (the apertures near S1 are narrower than the drawing line width, hence they appear to be linear and not boxy). The contours follow the 31 GHz emission, as in Fig. 1. The centre of the black circles indicates the positions of the early-type stars S1, SR3 and HD 147889 (see Fig. 4).

SL2. This resulted in SL1 spectra at two distinct positions in the S1 nebulosity, which we call ‘S1’ and ‘S1off’, as also shown in Fig. 3. The position ‘S1off’ is located at the northern edge of the IR nebulosity surrounding the early-type star S1. The solid angles covered by each IRS aperture are, in steradians:  $1.15 \times 10^{-8}$  in  $\rho$  Oph W,  $2.02 \times 10^{-8}$  in SR  $\sim 3$ , and  $4.96 \times 10^{-9}$  in both S  $\sim 1$  and S  $\sim 1\text{off}$ .

### 3.3 FEROS and University of South Wales-Mopra Spectrograph (UNSW-MOPS) observations

#### 3.3.1 FEROS

HD 147889 is the main source of excitation in  $\rho$  Oph W so an accurate measurement of its spectral type is necessary. HD 147889 is catalogued in SIMBAD as a single B2III/B2IV star (Houck & Smith-Moore 1988). However, Hafner & Meyer (1995) reported that HD 147889 is a close binary. The spectral types they quote are B2 for both components, and luminosity class IV and V. Unfortunately, Hafner & Meyer (1995) do not give details on their atmospheric models. Given the importance of HD 147889 for  $\rho$  Oph W, we undertook new echelle observations and up-to-date atmospheric modelling.

In order to precisely determine the UV field impinging on  $\rho$  Oph W, we acquired echelle spectroscopy of HD 147889 during two contiguous nights in 2008 May (ESO programme 081.C–2003). We used the FEROS echelle spectrograph, at the ESO 2.2-m telescope, which provides full coverage over 3500–9000 Å at  $R = 50\,000$ . We also found two spectra from 2006 February in the ESO archive (programme 076.C–0164).

#### 3.3.2 UNSW-MOPS

The UNSW-MOPS<sup>3</sup> spectrometer on the Mopra telescope, a 22-m single dish, allows the acquisition of area-spectroscopy data cubes up to  $\sim 0.6 \text{ km s}^{-1}$  in spectral resolution and with a bandwidth of  $\sim 2 \times 10^3 \text{ km s}^{-1}$  (in zoom mode).

Radio recombination lines (RRLs) are diagnostics of physical conditions. In particular, low-frequency carbon RRLs have been reported from  $\rho$  Oph and other PDRs in reflection nebulae (Pankonin & Walmsley 1978). We attempted to detect the high-frequency carbon RRL system of  $\rho$  Oph W using UNSW-MOPS. We acquired  $20 \times 20 \text{ arcmin}^2$  on-the-fly scans centred on  $\rho$  Oph W and the following rest-frame frequencies (in GHz): in the  $K$  band, C65 $\alpha$  23.41595, C66 $\alpha$  22.37532, C67 $\alpha$  21.39545, C68 $\alpha$  20.47197, C69 $\alpha$  19.60089, C70 $\alpha$  18.77853, C71 $\alpha$  18.00153, C72 $\alpha$  17.26682 and C73 $\alpha$  16.57156, and in the  $W$  band, C42 $\alpha$  85.73114 and C43 $\alpha$  79.95252. All nine  $K$ -band frequencies could be mapped simultaneously in zoom mode, for a total of 40 min. The  $W$ -band map represented 2 h.

Data reduction was carried out with the ‘LIVEDATA’ and ‘GRIDZILLA’ packages. We chose to resample the data cubes into 5 arcmin pixels. The  $1\sigma$  noise was  $0.366 \text{ MJy sr}^{-1}$  (or 43 mK) for C73 $\alpha$  and  $188 \text{ MJy sr}^{-1}$  (or 832 mK) for C42 $\alpha$ . No lines were detected.

### 3.4 Additional archive data

The *WMAP* satellite (Hinshaw et al. 2007) provides low-resolution images of  $\rho$  Oph in five bands at 23, 33, 41, 61 and 94 GHz, with average beam-widths of 0.88, 0.66, 0.51, 0.35 and 0.22 deg, respectively. Despite their low resolution, the *WMAP* data allow the extraction of the radio spectral energy distribution (SED).

### 3.5 Additional archive data

The Parkes-MIT-NRAO survey (PMN; Condon, Griffith & Wright 1993, as presented in *SkyView*, <http://skyview.gsfc.nasa.gov>) at 5 GHz traces H I free-free emission from H II regions. The PMN at 5 GHz is strongly affected by flux loss, or missing low spatial frequency due to high-pass filtering. The  $\rho$  Oph W region includes extended negatives, indicative of survey artefacts. We estimated the level of filtering artefacts in PMN by comparing with diffuse H II regions (selected from Lockman, Pisano & Howard 1996, hereafter LPH96) in the Effelsberg 2.7 GHz survey (Reich et al. 1990). We extract flux densities as in  $\rho$  Oph W (i.e. using a circular aperture 45 arcmin indiameter), and scale with a free-free index. The flux density recovered by PMN is 87 per cent in the case of relatively compact RCW 6 ( $\sim 6 \text{ arcmin}$ ), 25 per cent in LPH96 201.663+1.643 ( $\sim 15 \text{ arcmin}$ , see also the analysis in Dickinson et al. 2006) and only 6 per cent in LPH96 78.229+3.716 (a filament  $\sim 1 \text{ deg}$  long and  $\sim 15 \text{ arcmin}$  wide). It appears that the flux recovered by PMN in the case of  $\rho$  Oph W could be as low as 5–10 per cent.

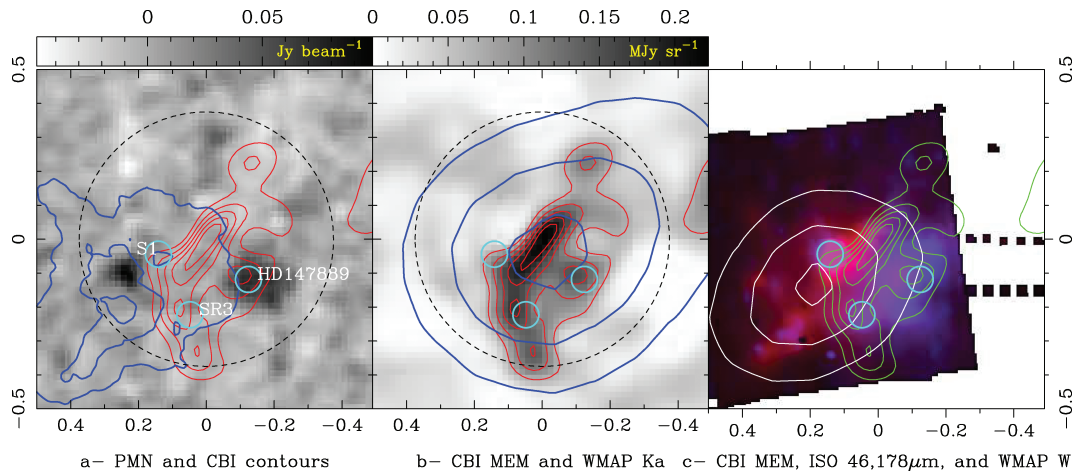
Another probe of the diffuse emission in  $\rho$  Oph is the Two-Micron All-Sky Survey (2MASS) <http://www.ipac.caltech.edu/2mass/>. The 2MASS- $K_s$  image produced by the Montage<sup>4</sup> mosaicing software, shown in Figs 3 and 5, is an interesting comparison point with the CBI image (see Sections 4.1 and 8.4.2).

Our analysis also makes use of the Southern H-Alpha Sky Survey Atlas (SHASSA; Gaustad et al. 2001). Another map useful in constraining the radio properties of  $\rho$  Oph is that of Baart, de Jager &

<sup>3</sup> <http://www.narrabri.atnf.csiro.au/mopra/mops/>

<sup>4</sup> <http://montage.ipac.caltech.edu/>





**Figure 4.** Morphological evidence ruling out standard dust or optically thin H I free-free as the origin of the 31 GHz emission.  $x$ - and  $y$ -axes show offset RA and Dec. from  $\rho$  Oph W, in degrees. The centre of the cyan circles indicates the positions of the early-type stars S1, SR3 and HD 147889. (a) CBI MEM contours overlaid on the PMN image (4.85 GHz), with  $A_V$  in blue contours at 10 and 20. (b) The CBI MEM image is shown in grey-scale in MJy sr $^{-1}$ , with the same contour levels as in Fig. 1. WMAP 33 GHz is shown in blue contours at 2.52, 2.99 and 3.37 K. (c) CBI MEM contours overlaid on an ISO colour map with 46  $\mu$ m in blue and 178  $\mu$ m in red. WMAP 94 GHz is shown in white contours at 1.21, 1.51 and 1.75 K.

Mountfort (1980), who report a 2.3 GHz map of the  $\rho$  Oph region, with a beam of 20 arcmin FWHM.

## 4 OBSERVED PROPERTIES

### 4.1 Morphology

The most conspicuous feature in the CBI MEM model, also shown in Fig. 4(b), is the  $\rho$  Oph W PDR, at the origin of coordinates. The WMAP 33 GHz contours in Fig. 4(b) confirm the bulk morphology of the CBI image.

We indicate in Fig. 4(a) the positions of the early-type stars S1 (Grasdalen, Strom & Strom 1973), SR3 (Elias 1978, EM\* SR3 in SIMBAD, also known as Elia 2-16), and HD 147889. These three stars, undetected in the CBI maps, excite the region and serve as reference points.

Inspection of Fig. 4(c) leads to the conclusion that the 31 GHz emission from  $\rho$  Oph is not the Rayleigh-Jeans tail of the submm-emitting large dust grains ('standard dust' hereafter). If the 31 GHz emission was due to standard dust, it should follow 94 GHz and 178  $\mu$ m. Both ISO 178  $\mu$ m (in red in Fig. 4c) and WMAP 94 GHz trace standard dust. But the CBI contours are offset to the north-west. The peak in WMAP 94 GHz is separated by 14 arcmin from the peak in the CBI model. The 94 GHz dust has been resolved into a system of cold dust clumps by submm bolometer arrays (e.g. Ridge et al. 2006; Young et al. 2006).

The PMN image in Fig. 4(a) shows two features: extended emission about HD 147889, which having an H $\alpha$  counterpart is a faint H II region, and the point source LFAM 21 (J162700.0 – 242640\*,  $\sim 60$  mJy at 5 GHz, Gagné, Skinner & Daniel 2004), undetected at higher frequencies. Also shown in Fig. 4(a) are contours at 10 and 20 of the visual extinction map  $A_V$  from Ridge et al. (2006).<sup>5</sup>  $A_V$  traces the total column density of material, i.e. the total mass density of the cloud.

Diffuse mid-IR emission ( $< 60 \mu$ m) from  $\rho$  Oph is interpreted as stochastic heating of VSGs (Bernard, Boulanger & Puget 1993).

In the dust model of Draine & Li (2007), VSGs are regarded as large polycyclic aromatic hydrocarbons (PAHs). Only the smallest VSGs, or PAHs, can reach spinning frequencies of  $\sim 30$  GHz. Thus for spinning dust, a close correspondence is expected between the CBI and mid-IR templates. There are indeed similarities between 31 GHz and ISO 46  $\mu$ m (in blue in Fig. 4c): both are found near HD 147889, while the far-IR emission is located about S1 and to the south-east.

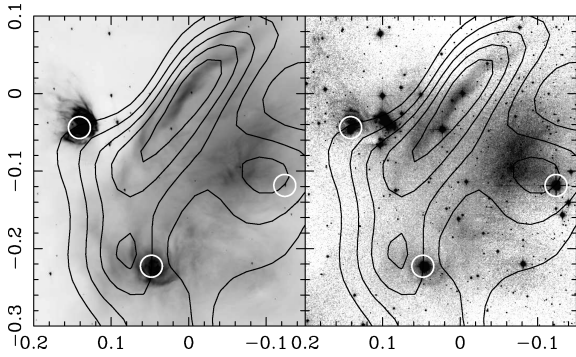
But there are important differences between the CBI image and the IR templates. In Fig. 3, we compare near- and mid-IR maps with the CBI contours. IRAC and MIPS aboard *Spitzer* provided high-resolution mosaics of  $\rho$  Oph at near- and far-IR wavelengths. The dust-heating flux from S1 produces the most conspicuous mid- and far-IR nebula in the entire  $\rho$  Oph region (e.g. the PAH 6.7- $\mu$ m band image in Abergel et al. 1996). Yet neither S1 nor SR3 has 31 GHz counterparts. It can also be noted that the photospheric IR emission is absent in the CBI maps (as is the case in LDN 1622, Casassus et al. 2006).

The IR emission shifts to longer wavelengths radially away from HD 147789: at increasing wavelengths, the emission from  $\rho$  Oph W moves to the north-east. It is surprising that the best match to the CBI contours of  $\rho$  Oph W turns out to be the 2.2  $\mu$ m diffuse emission in the 2MASS  $K_s$  band, shown in blue in Fig. 3, and in grey-scale in Fig. 5. The pointing uncertainty of the CBI is  $< 0.5$  arcmin (e.g. Casassus et al. 2006) – the phase calibrator J1626–298 was offset by only 0.2 arcmin from the phase centre. Thus, the CBI data are sensitive to the  $\sim 2$  arcmin translation in  $\rho$  Oph W, when seen in MIPS 24  $\mu$ m and 2MASS  $K_s$  band.

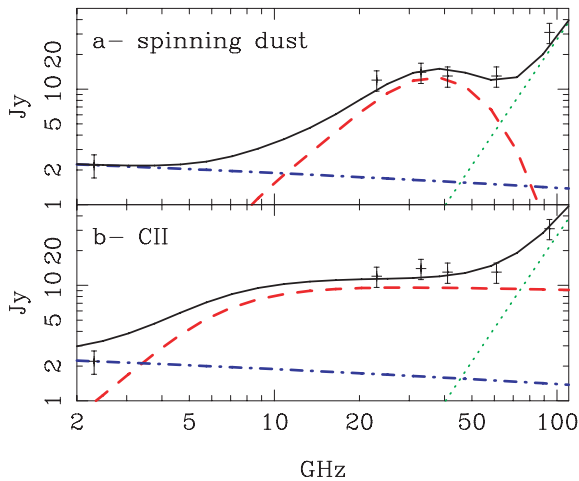
The only 2MASS counterpart to the CBI contours is the emission peaks along  $\rho$  Oph W. The north–south extension of the CBI contours to the east of SR3 is undetectable in 2MASS, but we note that this region has higher extinction than  $\rho$  Oph W (see Section 5.1).

Another conspicuous feature of the 2MASS image is the nebulousity about HD 147889, which is probably the near-IR counterpart to the diffuse H II region seen in PMN. An extended 2MASS source at J162622–242301, at  $(\Delta\alpha, \Delta\delta) \approx (+0.09, -0.04)$  and between S1 and W, corresponds to the disc-like envelope surrounding the young stellar object GSS 30 IRS1 (Chrysostomou et al. 1996).

<sup>5</sup> <http://www.cfa.harvard.edu/COMPLETE>



**Figure 5.** The 2MASS–CBI correlation. The image is an overlay of the CBI MEM contours on the IRAC 8  $\mu$ m (left-hand panel) and 2MASS  $K_s$ -band images (right-hand panel).  $x$ - and  $y$ -axes show offset RA and Dec. from  $\rho$  Oph W, in degrees. It may be appreciated that the 2MASS and IRAC 8  $\mu$ m emissions correlate with 31 GHz in  $\rho$  Oph W.



**Figure 6.** The cm-wave spectrum in a 45.5 arcmin circular aperture centred on  $\rho$  Oph W. All data points are extracted from the *WMAP* images, except for the 2.3 GHz point, which is taken from Baart et al. (1980, see section 4.4). The solid black line is a fit to the data that include a modified blackbody, in green dotted line (with  $T_d = 23$  K and  $\beta = 1.7$ ), a diffuse free–free component, shown as a dash–dotted blue line, and in red-dashed line either a spinning dust component (a) spinning dust, for the ‘DC’ environment, or a cold C I thermal component stemming from an ensemble of PDR sheets seen edge-on (b) C II.

## 4.2 Spectrum

In Fig. 6, we have constructed the spectral energy distribution of  $\rho$  Oph A using the flux densities given in Table 1. The *WMAP* flux densities are extracted from a circular aperture equal to the CBI PB, without background correction.

It is difficult to extract spectral index information from the 10 CBI channels because the  $u$ ,  $v$  coverage varies with frequency: flux loss, or the fraction of the flux density in the CBI 45 arcmin aperture that is filtered out, varies with both channel frequency and sky image. A template close in morphology to the 31 GHz emission could have been used to extract accurate channel flux densities. But no such template is available. The cross-correlation between the CBI data and simulated visibilities on the prior image shown in Fig. A2(e) gave high reduced  $\chi^2$  values ( $\sim 2.4$ ) and  $r$  correlation coefficients of  $\sim 0.6$ . The MEM model itself cannot be

**Table 1.** Observed flux densities inside the half-maximum contour of the CBI PB. Rms uncertainties in the flux densities are of the order of 20 per cent.

| $\nu^a$    | 2.3 <sup>c</sup> | 23 <sup>d</sup> | 31 <sup>e</sup> | 33 <sup>d</sup> | 41 <sup>d</sup> | 61 <sup>d</sup> | 94 <sup>d</sup> |
|------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $F(\nu)^b$ | 2.2              | 12              | 7.9             | 14              | 13              | 13              | 31              |

<sup>a</sup>Frequency in GHz.

<sup>b</sup>Flux density in Jy, with uncertainties of 20 per cent.

<sup>c</sup>From Baart et al. (1980).

<sup>d</sup>From *WMAP*.

<sup>e</sup>CBI flux density before correcting for flux loss.

used as a template in this case because it is limited in resolution by the dynamic range of the data.

The submm continuum in  $\rho$  Oph A can be estimated from the *WMAP* 94 GHz and far-IR points, as a single modified blackbody with an emissivity index  $\beta$ . For this purpose, we used the IRIS (Miville-Deschenes & Lagache 2005) reprocessing of the *IRAS* survey (Wheelock et al. 1994), and extracted flux densities in a circular aperture equal to the CBI PB (the *ISO* images lack coverage in the eastern side of the photometric aperture). The observation of a submm flux density is required to constrain the value of  $\beta$ . We did not use the Submillimetre Common-User Bolometer Array (SCUBA) maps of  $\rho$  Oph because they are strongly filtered. We estimated by comparison with the expected submm continuum that the diffuse emission that is filtered out of the bolometer data in a 45 arcmin aperture can amount to  $\sim 85$  per cent.

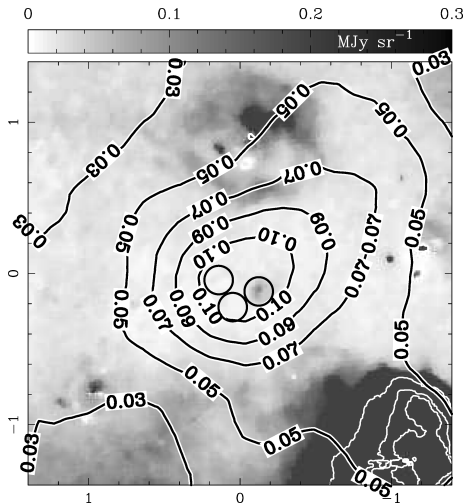
## 4.3 CBI flux loss

The CBI image is not sensitive to the lowest spatial frequencies; uncertainties in the comparison data are approximate and stem mostly from mismatched angular scales, not thermal noise. In particular, the *WMAP* beam at 33 GHz is approximately Gaussian with FWHM  $\sim 49$  arcmin (Bennett 2003), so that the emission within the CBI beam is somewhat convolved with the surroundings. In turn, part of the flux at low spatial frequencies is filtered out in the interferometer data.

We have simulated CBI observations on two templates: IRAC 8  $\mu$ m, after removing stars by median filtering and IRIS1, a 12  $\mu$ m template (Miville-Deschenes & Lagache 2005). After reconstruction with a blank prior (as in Section A), we find that 41.3 per cent of the IRAC 8  $\mu$ m flux within the CBI PB is recovered by the simulation and 51.4 per cent in the case of IRIS1. The same algorithm applied to the CBI visibility produces the image shown on Fig. A2(d), and a flux density of 5.0 Jy, which when compared to 14 Jy in *WMAP* 33 GHz implies that the fraction of flux density recovered in the blank-prior reconstructions is 35 per cent. But the image prior used in our best CBI reconstructions allow us recovering part of the extended emission. Comparison of the flux density obtained from the restored image on Fig. A2(a) and with *WMAP* 33 GHz shows that, with the use of a prior, 56 per cent of the signal is recovered by the CBI.

## 4.4 H I free–free

The *WMAP* 33 GHz and SHASSA images shown in Fig. 7 illustrate that  $\rho$  Oph W is superposed on an extended background, which is probably the free–free counterpart to the H $\alpha$  emission. There are, however, intriguing features in Fig. 7: the bright H $\alpha$  source to the south-west (a bright H II region surrounding  $\sigma$  Sco, known as Gum 65 or S 9) should correspond to 33 GHz free–free levels at least a



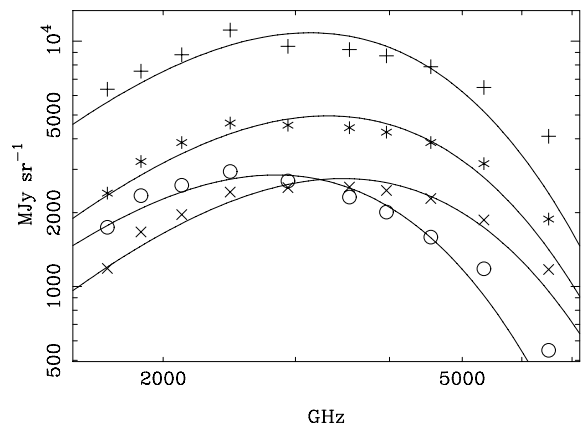
**Figure 7.**  $H\alpha$  and  $H\text{I}$  continuum towards  $\rho$  Oph. The figure shows an  $H\alpha + [\text{NII}]$  image of the  $\rho$  Oph region, as extracted from SHASSA, and scaled to the corresponding  $T_e = 8000$  K free-free continuum at 33 GHz, in  $\text{MJy sr}^{-1}$ , without correction for reddening. The black and white contours follow WMAP 33 GHz, also in  $\text{MJy sr}^{-1}$ . The SHASSA emission from Gum 65 to the south-west is traced in white contours at 1.0, 5.0 and 10  $\text{MJy sr}^{-1}$ . The circles indicate the positions of S1, SR3 and HD 147789.  $x$ - and  $y$ -axes show offset RA and Dec. from  $\rho$  Oph W, in degrees.

factor of 10 higher than seen in WMAP Ka. We believe this is due, in part, to dilution in the WMAP beam, but also to  $[\text{NII}]$  doublet contamination in the SHASSA filter, which can be of the order of 50 per cent in photoionized nebulae (e.g. in the Helix, see section 2.3 in Casassus et al. 2004), or even higher in shocks. Nitrogen is found singly ionized in the outer bounds of ionization-bounded nebulae, which are the surface regions sampled by the (extinction sensitive) SHASSA filter.

In the 2.3 GHz map of Baart et al. (1980), the CBI PB lies in a region of a uniform emission, with a brightness temperature of  $\sim 100$  mK. The integrated flux density inside our photometric aperture is thus  $\sim 2.2$  Jy at 2.3 GHz or  $\sim 1.7$  Jy at 31 GHz.<sup>6</sup>

The PMN flux density in the 45 arcmin photometric aperture is essentially zero. Yet the SHASSA survey shows substantial diffuse  $H\alpha$  in the region of  $\rho$  Oph W. The total  $H\alpha$  flux in the CBI PB, if due to the diffuse 8000 K plasma discussed by Dickinson, Davies & Davis (2003), implies that the free-free level at 5 GHz should be at least  $\sim 2.5$  Jy. After correction for the average value of extinction inside the CBI beam but outside the dark cloud itself,  $E(B - V) \approx 1-3$  (Schlegel, Finkbeiner & Davis 1998), or  $A_V = 3-9$  for  $R_V = A_V/E(B - V) = 3.1$ , the predicted level of free-free emission could reach the values of the order of  $\sim 10$  Jy. Since the 2.3 GHz flux density inferred from Baart et al. (1980) is somewhat less than the minimum allowed by SHASSA, we conclude that the diffuse emission seen by SHASSA is also strongly contaminated by  $[\text{NII}]$ .

<sup>6</sup> Given that the CBI flux density measured from the blank-prior CBI image Fig. A2(d) is 5.0 Jy while WMAP 33GHz sees 14 Jy, of which 1.7 Jy are diffuse free-free, we obtain that the CBI recovers 40 per cent of the non-free-free emission (consistent with Section 4.3, see also Section 8.5).



**Figure 8.** Representative ISO-LWS specific intensity spectra, at four selected positions in  $\rho$  Oph:  $\rho$  Oph W (circles), S1 (pluses), HD 147889 (crosses) and SR3 (asterisks, scaled by a factor of 1.8 for clarity). The solid lines are best-fitting grey-body spectra, as discussed in the text and summarized on Fig. 9.

## 5 DUST EMISSION

### 5.1 IR emission from dust grains

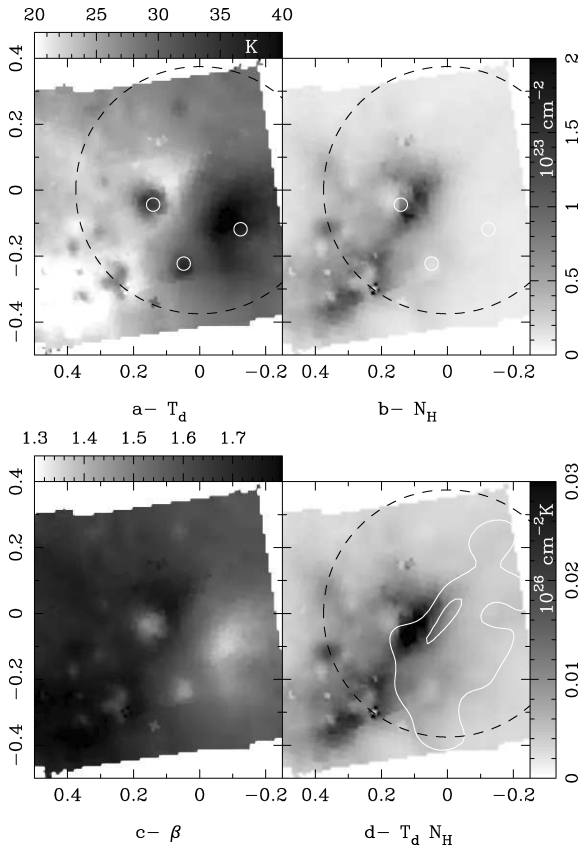
Bulk physical properties of the dust in  $\rho$  Oph can be obtained by fitting modified black bodies to the spectra extracted from each spatial pixel of the ISO data cube. A single modified blackbody turns out to give a fairly good fit, despite expected temperature gradients, especially from stochastic heating of the smaller grains (whose emission, as traced by IRAC 8  $\mu\text{m}$  for instance, is very different from that of the larger grains emitting at 100  $\mu\text{m}$ ).

The grey-body parameters are the opacity at 100  $\mu\text{m}$ ,  $\tau_{100}$  and  $T_d$ , the dust temperature. The dust emissivity index is determined by its anticorrelation with dust temperature, as reported by Dupac et al. (2003):  $\beta = 1/(0.4 + 0.008T_d)$ .  $\tau_{100}$  is related to  $N_H$ , the H-nucleus column density, by  $N_H = 4 \times 10^{24}(\lambda/100 \mu\text{m})^\beta \tau_{100} \text{ cm}^{-2}$  (Draine & Lazarian 1999). The example IR spectra are shown on Fig. 8.

The resulting temperatures, column densities and dust emissivities are shown in Figs 9(a–c). The maximum value of  $N_H$  in Fig. 9(b) is  $2.3 \times 10^{23} \text{ cm}^{-2}$ , and the temperature varies over 20–40 K. The early-type stars S1 and SR3 (see Section 8.1) are coincident with temperature peaks, as expected from grains in radiative equilibrium with the stellar UV radiation. But neither S1 nor SR3 corresponds to peaks in column density.  $N_H$  peaks close to S1, but its morphology follows that of the  $\rho$  Oph A molecular core. Therefore, the IR circumstellar nebulae about S1 and SR3 are radiation bounded rather than matter bounded.

The total mass in the ISO field,  $M_T = m_p D^2 \int d\Omega N_H$ , is  $922 M_\odot$ . Considering the numerous assumptions implicit in converting dust emissivities to H-nucleus densities, this mass estimate is consistently close to  $\sim 2500 M_\odot$  given by Liseau et al. (1995, 1999). But the mass seen by ISO is much less than the  $7400 M_\odot$  derived from the near-IR extinction (Ridge et al. 2006). Perhaps the extinction has been overestimated, or there are very cold regions in  $\rho$  Oph not sampled by ISO.

We also obtain a mass of  $65 M_\odot$  for  $\rho$  Oph W, if its extension is defined by a 31 GHz intensity threshold of  $0.124 \text{ MJy sr}^{-1}$  in the MEM model (see Fig. 1). The mass above a 31 GHz intensity threshold of  $10^{-3} \text{ MJy sr}^{-1}$  is  $359 M_\odot$ .



**Figure 9.** Axes labels and symbols follow from Fig. 4. (a) Dust temperature in grey-scale, the CBI PB and the positions of S1, SR3 and HD 147789 are indicated. (b) The H-nucleus column density inferred from the far-IR *ISO* data. (c) Dust emissivity (or temperature spectral index) inferred from the  $\beta$ – $T_d$  anticorrelation of Dupac et al. (2003). (d) Grey-scale image of the product of the H-nucleus column density  $N_H$  times the dust temperature  $T_d$ , in units of  $10^{26} \text{ m}^{-2} \text{ K}$ . Also shown are the lowest and highest contours of the CBI MEM models, at  $0.067$  and  $0.197 \text{ MJy sr}^{-1}$ .

## 5.2 Magnetic dust

The magnetic dipole emission from magnetic fluctuations in ferromagnetic grains results in a cm-wave enhancement of the grain emissivity (Draine & Lazarian 1999). At cm-wavelengths classical (not VSG) dust is in the Rayleigh-Jeans regime, so that magnetic dust emission should be proportional to the product of the column of ferromagnetic grains and their temperature. Under the assumption that ferromagnetic grains, if they exist, are uniformly mixed with the rest of the dust, the CBI image should be proportional to the product of the dust column  $N_d$  and temperature  $T_d$  for constant dust-to-gas ratio ( $N_d \propto N_H$ ).

It can be seen in Fig. 9(d) that the morphology of the CBI MEM contours is very different from that of the product  $N_H T_d$ , which instead follows the far-IR emission. Since we cannot find any reason why ferromagnetic grains, if they exist, would be found preferentially in  $\rho$  Oph W, we conclude that magnetic dust is inconsistent with the *ISO* data.

Another difficulty for magnetic dust is the lack of detectable polarization. Draine & Lazarian (1999, their fig. 9) predict polarization fractions  $f$  from perfectly aligned ferromagnetic grains. For their hypothetical material ‘X4’, the predicted fraction at 31 GHz is at least  $f = 25$  per cent. X4 is the only material considered by Draine & Lazarian (1999) whose emissivities reach the levels required by

the anomalous foreground. Martin (2007, his table 2) quantifies the degree of grain alignment through a reduction factor  $R$ , which ranges from 0.19 to 0.67 for a wide variety of grain geometries. Thus, the polarization expected from magnetic dust is at least 4.7 per cent. However, the CBI data place a strict  $3\sigma$  polarization upper limits of 4.8 per cent in the specific intensity at the peak in  $\rho$  Oph W – and only 1 per cent in the 45 arcmin photometric aperture.

## 5.3 Spinning dust

The spinning dust emissivities, being linear proportional to the density  $n_H$  (as dust emissivities in general), could be more important in diffuse media relative to emission mechanisms based on binary encounters, which are quadratic in  $n_H$ . With its very steep low-frequency spectral index,  $\alpha \sim +3$ , spinning dust explains the lack of low-frequency emission.

Spinning dust gives a remarkably good fit to the  $\rho$  Oph W SED (see Fig. 6) if  $\beta = 1.7$ , which is within the range of observed values (Dupac et al. 2003). Higher emissivities result in a drop at  $\sim 60$ – $90$  GHz, which misses the *WMAP* 94 GHz data point. The best-fitting spinning dust spectrum is obtained for the ‘DC’ case of Draine & Lazarian (1998b). Spinning dust requires that the product  $n_H f \sim 10^5 \text{ cm}^{-3}$ , where  $f$  is the volume filling factor.

No local 31 GHz peaks are observed at the positions of S1 and SR3. Although part of the emission surrounding S1 and SR3 could be scattered light in IR reflection nebulae, the *Spitzer* IRS area-spectroscopy highlights very bright PAH bands in the circumstellar nebulae around S1, SR3 and  $\rho$  Oph W. The absence of S1 and SR3 in the CBI data may be inconsistent with spinning dust, since the proximity of early-type stars should result in high spinning dust emissivities, provided VSGs are not depleted. The environment around S1 corresponds to the ‘RN’ case of Draine & Lazarian (1998b): the Castelli & Kurucz (2003) model atmospheres give a UV flux parameter  $\chi \approx 5000$  (as defined in Draine & Bertoldi 1996). In this case, the predicted spinning dust emissivity per unit H-nucleus column density is  $10^{-17} \text{ Jy sr}^{-1} \text{ cm}^2$  at 31 GHz. The observed column densities towards S1 are  $10^{23} \text{ cm}^{-2}$  (see Section 5.1), so the emergent 31 GHz intensity from S1 should be  $1 \text{ MJy sr}^{-1}$ , which is a factor of 10 larger than the observed peak 31 GHz intensities (which are found in  $\rho$  Oph W and not towards S1), and a factor of 40 larger than a strict upper limit of  $25 \times 10^{-3} \text{ MJy sr}^{-1}$  in S1 (see Table 2).

We can take into account the possibility of VSG depletion by examining the ratios of PAH and 31 GHz intensities. The dust-heating radiation field can be parametrized, as in Draine & Li (2007),

**Table 2.** Observations derived from the CBI and PAH  $11.3 \mu\text{m}$  intensities in the *Spitzer* IRS apertures.

|              | $R \times U^{a,b}$ | $U^c$  | $I_{31 \text{ GHz}}^d$ | $I_{\text{PAH}}^e$ | $d^f$ |
|--------------|--------------------|--------|------------------------|--------------------|-------|
| $\rho$ Oph W | $27.5 \pm 2.7$     | 66     | $2.2 \pm 0.2(-1)$      | $3.3(-6)$          | 10.4  |
| SR3          | $<1.2 \pm 3.2$     | $<238$ | $3.2 \pm 8.4(-3)$      | $3.8(-6)$          | 0.97  |
| S1           | $1.0 \pm 4.9$      | 1076   | $1.7 \pm 8.4(-3)$      | $1.1(-5)$          | 0.92  |
| S1off        | $<1.0 \pm 1.1$     | 246    | $5.2 \pm 5.9(-4)$      | $8.0(-7)$          | 1.92  |

<sup>a</sup> $R = I_v(31 \text{ GHz})/I_{\text{PAH}}(11.3 \mu\text{m})$ .

<sup>b</sup>Normalized to the value in the S1off aperture.

<sup>c</sup>Unattenuated UV field parameter.

<sup>d</sup>CBI MEM specific intensities in  $\text{MJy sr}^{-1}$ .

<sup>e</sup>PAH  $11.3 \mu\text{m}$  intensity in  $\text{W m}^{-2} \text{ sr}^{-1}$ .

<sup>f</sup>Projected distance from exciting star, in arcmin.

<sup>g</sup>Parentheses indicate a power of 10 exponent multiplying both the average values and their uncertainties.

by scaling the interstellar radiation field in the solar neighbourhood (Mathis, Mezger & Panagia 1983). The dimensionless parameter  $U$  measures the average intensity of radiation in  $4\pi$  sr, integrated from 0.09 to 8  $\mu\text{m}$ . The spinning dust emissivity per nucleon is remarkably independent of the intensity of UV radiation (Draine & Lazarian 1998b, their fig. 9), while the flux in the PAH bands is linear in  $U$  (for instance see fig. 13 in Draine & Li 2007). Therefore, if PAHs are involved in the 31 GHz emission, the intensity ratio  $R = I_{\nu}(31 \text{ GHz})/I_{\text{PAH}}(11.3 \mu\text{m})$  should be inversely proportional to  $U$ .  $R$  is independent of the PAH abundance since it enters linearly both in  $I_{\nu}(31 \text{ GHz})$  and  $I_{\text{PAH}}$ . Given that the spinning dust emissivities per nucleon (Draine & Lazarian 1998b) vary by at most a factor of 10 for environments with extremely different physical conditions, we can conservatively assume that  $R \times U$  should not vary by more than a factor of 10 when comparing widely different regions.

The IRS data allow extracting fluxes for the PAH band at 11.3  $\mu\text{m}$ ,  $F_{\text{PAH}}(11.3 \mu\text{m})$ , in two rectangular apertures near S1, one near SR3 and one in  $\rho$  Oph W, indicated as black and dotted-white boxes on Fig. 3. We subtracted a linear continuum under the 11.3- $\mu\text{m}$  band, as well as a sky background PAH 11.3- $\mu\text{m}$  intensity of  $2 \times 10^{-7} \text{ W m}^{-2} \text{ sr}^{-1}$ , obtained by scaling the observed PAH intensities following the IRAC 8- $\mu\text{m}$  image. The background PAH intensity is only five times fainter than the observed in the S1off aperture ( $9.98 \times 10^{-6} \text{ W m}^{-2} \text{ sr}^{-1}$  before background correction).

Until we obtain higher resolution data, our estimates of the 31 GHz specific intensities  $I_{31 \text{ GHz}}$  are dependent on the MEM model. In the brightest regions, as in  $\rho$  Oph W, we assume 10 per cent uncertainties. The product of the IRS extraction solid angle times the CBI intensity at the centroid of the  $\rho$  Oph W aperture is an approximation to  $F_{\nu}(31 \text{ GHz})$ , the 31 GHz flux density. For the fainter regions, we use the prior that the emission is due to spinning dust (which is the aim of this test): the circumstellar nebulae around S1 and SR3 are  $\sim 3$  arcmin in diameter and so should appear as point sources in the CBI maps. A formal fit to the MEM visibility residuals for point sources at the locations of S1 and SR3 gives 31 GHz flux densities of  $1.3_{-4}^{+7}$  and  $2.0_{-3}^{+7}$  mJy, respectively, which can be converted into intensities assuming uniform nebulae. For S1off, we scale the 31 GHz intensity in the S1 aperture by the product of PAH 11.3  $\mu\text{m}$  intensities times  $U$  (i.e. as the inverse-squared projected distance).

The unattenuated intensity of dust-heating radiation, parametrized by  $U$ , can be evaluated at the projected distance from the exciting stars to the centre of each IRS aperture, using the model atmospheres of Castelli & Kurucz (2003)<sup>7</sup> and the stellar parameters given in Section 8.1. We obtain the properties listed in Table 2. Taking into account the uncertainties, the product  $R \times U$  is consistent with variations by less than a factor of 10. A marginal exception may be the comparison between S1off and  $\rho$  Oph W, where the 31 GHz uncertainties are reduced relative to S1 because of the hypothesis that the 31 GHz intensity in S1off scales with  $U \times I_{\text{PAH}}$  relative to S1. In the S1off –  $\rho$  Oph W comparison, taking  $3\sigma$  shifts in  $R \times U$  can bring its variations down to a factor of 4, and so in agreement with spinning dust.

A source of uncertainty is the correction for UV attenuation, which may affect all lines of sight in Table 2. Attenuation is most important for S1off, since the circumstellar nebula around S1 are probably ionization bounded (see Section 5.1). The value in Table 2 is therefore an upper limit. Similarly for SR3, which is obscured in the visible. On the other hand, S1 is bright in visible, so its

circumstellar nebula stems from the walls of a wind-blown cavity driven by S1 into the  $\rho$  Oph A core. Thus, UV attenuation should be negligible in the S1 IRS aperture. According to the model of Liseau et al. (1999), HD 147889 is separated from LDN 1688, so that its UV luminosity should be fairly unattenuated towards  $\rho$  Oph W.

Could physical conditions in S1 and SR3 be such that spinning dust is quenched by mechanisms not contemplated by Draine & Lazarian (1998b)? The possibility of vanishing grain polarization can be discarded. According to the PAH ionization diagnostic of Draine & Li (2001, their fig. 16), the PAH band fluxes given by Boulanger et al. (1996), extracted from an aperture 10 arcmin north of  $\rho$  Oph W, correspond to neutral PAHs. Any photoelectric charge expected in the intense UV fields of S1 and SR3 increases quadratically the spinning dust emissivity (equation (11) in Draine & Lazarian 1998b). But it could be that the radiation field from HD 147889 is sufficiently hard to boost the spinning dust emissivity through VSG ionization, and yet not completely deplete the grains. We used the IRS spectra to place S1 in the PAH-colour diagram of Draine & Li (2001, their fig. 16), finding it lies close to  $\rho$  Oph W – i.e. at the locus of neutral PAHs. Another interesting possibility is that perhaps PAH rotation brakes to lower frequencies in the vicinity of SR3 and S1, maybe as a consequence of grain alignment in intense magnetic fields (which are not considered in Draine & Lazarian 1998b).

Yet another alternative to explain the lack of 31 GHz emission from S1 and SR3 is that the spinning VSGs are not related to PAHs, so that they do not emit in the PAH bands. For instance, they could perhaps be nano-silicates (e.g. Witt, Gordon & Furlton 1998) very fragile to UV radiation, or maybe chain-like carbonaceous molecules. If so the existing spinning dust models must be revised, since they are calculated for aromatic carbonaceous grains, including a population of sheet-like grains (i.e. PAHs).

Iglesias-Groth (2005, 2006) has proposed hydrogenated fullerenes as a carrier for the 31 GHz emission. Perhaps the polarized fullerenes could be depleted near S1 and SR3. But at present we lack diagnostics of such fullerenes to test this alternative. As proposed by Webster (1992), fullerenes could also be the carriers of the diffuse interstellar bands (DIBs). Spectroscopy of stars in the background of  $\rho$  Oph W is required to examine the possibility of a link between the DIBs and the anomalous foreground.

## 6 C I CONTINUUM

### 6.1 Cold plasmas in PDRs

The outer layers of molecular clouds are composed of atomic hydrogen. The ionization energy of  $\text{H}_2$  is 15.4 eV, while the  $\text{H}_2$  dissociation continuum starts at 14.7 eV, both of which are attenuated by  $\text{H I}$  ionization. In practice,  $\text{H}_2$  photodissociation occurs in the radiative cascade following bound-bound absorption of photons with discrete energies in the range 11.3–13.6 eV (e.g. Tielens 2005). Thus, the bulk of the  $\rho$  Oph cloud is largely neutral.

All photons harder than 13.6 eV are absorbed in the vicinity of HD 147889, producing a  $\sim 5$  arcmin diffuse  $\text{H II}$  region (about 0.2 pc in physical size). Yet a residual charge density exists in the neutral layers of  $\rho$  Oph exposed to radiation from HD 147889. C-ionizing photons with energies in a continuum between 11.3 and 13.6 eV penetrate deep inside the exposed neutral layers of  $\rho$  Oph W. C-ionization extends into molecular layers. Other metals with ionization potentials inferior to 13.6 eV, most notably sulfur, also contribute to the ionization fraction  $x = n_e/n_{\text{H}}$ , but in proportion to their abundance.

<sup>7</sup> As given in <http://wwwuser.oat.ts.astro.it/castelli/grids.html>.



Another source of ionization in molecular clouds is the cosmic ray ionization of  $\text{H}_2$ . For an isolated molecular cloud subjected to the average interstellar cosmic ray ionization rate  $\zeta$ , molecular line observations have yielded  $x \approx 10^{-8}$ . Specifically for  $\rho$  Oph, Wootten, Snell & Glassgold (1979) give  $x = 2.6 \times 10^{-7}$ . However, the molecular line diagnostics in Wootten et al. (1978) trace the dense core in  $\rho$  Oph A, and may not be representative of  $\rho$  Oph W. Is it possible that in  $\rho$  Oph W the vicinity of HD 147889 increases  $\zeta$  sufficiently so that  $\text{H}_2^+$  also contributes to  $x$ ? Probably not, since the ratio of projected distances between  $\rho$  Oph A and  $\rho$  Oph W to HD 147889 is  $\sim 2$ , which would only raise  $\zeta$  by a factor of 4, and yields an  $x$  value still two orders of magnitude below the carbon abundance.

## 6.2 C I model

Here, we estimate the expected intensity levels of free-free emission due to  $\text{C}^+$  encounters with free electrons (C I continuum) from the cold plasma in  $\rho$  Oph W. Although the ionization fraction in PDRs is very small,  $x \sim 10^{-4}$ , the free-free emissivity is  $\propto 1/\sqrt{T_e}$  and biased towards lower temperatures. A temperature of  $\sim 50$  K is representative of most of the emissivity-weighted C II region in the models of Liseau et al. (1999) and Habart et al. (2003). A shortcoming of this model is that it requires a clumpy medium with very high H-nucleus densities, of the order of  $10^7 \text{ cm}^{-3}$ , and small volume filling factors,  $f \sim 10^{-4}$ .

The available data lead us to consider an ensemble of dense neutral clumps, with an ionization fraction  $x \sim 10^{-4}$  (the abundance of C), a total extent  $\theta_N \approx 20$  arcmin and covering a solid angle  $\Omega_N \approx \pi(\theta_N/2)^2$ . Since  $\rho$  Oph W is undetected in the HRAO data of Baart et al. (1980), with a 20 arcmin beam and an rms sensitivity of 30 mK, at 2.3 GHz the total emission from the clumps should be less than  $F_c(2.3 \text{ GHz}) \approx \Omega_N \times 3I_{\text{rms}}(2.3 \text{ GHz}) \approx 2 \text{ Jy}$ . The total flux density seen by *WMAP* at 33 GHz and not attributed to H I free-free is 12.3 Jy. Thus, the clumps must be optically thick at 2.3 GHz, and cover a solid angle inferior to  $\Omega_c \approx F_c(2.3 \text{ GHz})/B_\nu(2.3 \text{ GHz}, T_e = 20 \text{ K}) \approx \pi 1.5^2 \text{ arcmin}^2$ , where  $B_\nu$  is the Planck function. Additionally, the clumps, while still optically thick at 5 GHz, are not detected in PMN, with a beam  $\theta_{\text{PMN}} = 3.7$  arcmin FWHM and an rms noise of  $I_{\text{PMN}} \sim 100 \text{ mJy beam}^{-1} = 0.67 \text{ MJy sr}^{-1}$ .<sup>8</sup> Therefore, an individual clump must be beam-diluted in PMN and cover a solid angle less than  $[I_{\text{PMN}}/B_\nu(5 \text{ GHz}, 20 \text{ K})]\{\pi/[4 \ln(2)]\}\theta_{\text{PMN}}^2 \approx 3 \text{ arcmin}^2$ .

As discussed in Section 4.2, the CBI sees about 30–40 per cent<sup>9</sup> of the total 31 GHz emission. The clump distribution should be sufficiently dense so as to mimick a uniform signal at CBI resolutions, while also extending to  $\theta_N$ . Thus, the interclump separation should be (i) less than 8 arcmin, the highest spatial frequency in the CBI  $uv$ -plane for the configuration used here and (ii) greater or similar to the PMN beam. To make headway, we will assume a number of clumps  $N_c = (\theta_N/\theta_{\text{PMN}})^2 \approx 30$ .

A plane-parallel geometry seen edge-on gives the highest clump opacities. To maximize the cold free-free opacity given an electron density, each clump would have to be  $\theta_{\text{PMN}}$  in length, equally deep,

and only  $\Omega_c/(N_c\theta_{\text{PMN}}) \approx 4$  arcsec wide. Higher densities alleviate the need for such large aspect ratios.

What is the density required to explain the 31 GHz flux density with a cold plasma, if we ignore the lower frequency data? In a uniform disc nebula 10 arcmin in diameter, and equally deep, with a C II region temperature of 150 K, we find that electron densities of  $n_e = 60 \text{ cm}^{-3}$  reach the observed 31 GHz level. The same result is arrived at by fixing the opacity profile to that of the CBI MEM model. Thus, H-nucleus densities of only  $n_H \sim 10^5\text{--}10^6 \text{ cm}^{-3}$  (within the range observed in  $\rho$  Oph W, see Section 8.2) account for all of the CBI flux.

## 6.3 Spectral energy distribution fit

The C I continuum model shown in Fig. 6(b) consists of a clump ensemble with  $N_c = 30$ , an electron density of  $750 \text{ cm}^{-3}$  and  $T_e = 20$  K. Each clump is a narrow sheet only 2 arcsec wide,<sup>10</sup> 3.7 arcmin long and equally deep. The corresponding volume filling factor is  $f \sim 10^{-4}$ . Uniform disc clumps, with equal depth and diameter and subtending the same solid angle as the sheets, would require electron densities of  $2200 \text{ cm}^{-3}$ . We favour a sheet-like geometry because of the considerations in Section 8.1: the thin sheet geometries could result from limb-brightening of a C II shell centred on HD 147889.

The total H-nucleus densities required by the C I model, whatever the geometry of the clumps, are of the order of  $\sim 10^7 \text{ cm}^{-3}$ , if all of C is ionized. The corresponding C II region mass is  $153 M_\odot$  for sheets, or  $45 M_\odot$  for discs, both of which are consistently less than the total mass enclosed by regions with finite  $I_{31 \text{ GHz}}$  (see Section 5.1).

In order to further test the C I continuum model, we searched the Australia Telescope Compact Array (ATCA) archive for pointings near  $\rho$  Oph W.  $\rho$  Oph 10 (also known as Doar 21; Falgarone & Gilmore 1981) was observed in array configuration C397, at frequencies of 1376, 2378, 4800 and 8640 MHz.<sup>11</sup> The phase centre lies in the 31 GHz  $\rho$  Oph W ridge, 2.2 arcmin south of the peak. At 4.9 GHz, the ATCA primary beam is 5 arcmin. Yet no clumpy medium is detected with a noise of  $5 \text{ mJy beam}^{-1}$ . Clearly, the putative C I clumps, if they exist, should be beam-diluted even inside the  $12 \times 7 \text{ arcsec}^2$  beam: the optically thick flux density in one synthetic beam is 160 mJy, if  $T_e = 20$  K. Very thin sheets,  $\sim 1$  arcsec wide, could still fit in.

## 7 RADIO RECOMBINATION LINES

Radio recombination lines (RRLs) are concomitant to free-free continua. Carbon RRLs have indeed been observed towards  $\rho$  Oph, albeit at low resolutions (Brown & Knapp 1974). Here, we provide upper limits on the RRL system in  $\rho$  Oph W, which require rather cold C II regions ( $T_e \sim 20\text{--}50$  K).

### 7.1 RRL data from the literature

Pankonin & Walmsley (1978) examined the most complete set of RRL data towards  $\rho$  Oph to date. They mapped the neighbourhood of S1, but did not extend their coverage to  $\rho$  Oph W, unfortunately. The highest frequency RRLs considered by Pankonin & Walmsley (1978) are C90 $\alpha$  and C91 $\alpha$ , at  $\sim 9$  GHz, which they interpreted as stemming from circumstellar gas about S1, with electron densities  $n_e \sim 15 \text{ cm}^{-3}$  and  $T_e \sim 150$  K. This circumstellar C II region was

<sup>8</sup> In which we have taken into account correlated pixels with a factor of  $\sqrt{N_{\text{beam}}}$ , where  $N_{\text{beam}}$  is the number of pixels that fall in one 3.7 arcmin beam.

<sup>9</sup> This is the ratio of 31 GHz flux densities obtained without the use of a prior to the *WMAP* 33 GHz flux densities.

<sup>10</sup> We chose 2 instead of 4 arcsec to better accommodate the 2.3 GHz point.

<sup>11</sup> ATCA programme C397, PI E. Feigelson.



inferred to be less than  $\sim 2$  arcmin in diameter, and surrounded by a diffuse halo with  $n_e \sim 1 \text{ cm}^{-3}$ , traced by the lower frequency carbon RRLs. The continuum level expected from such a C II region is  $\sim 1 \text{ mJy}$  at 31 GHz, consistent with its absence from the CBI MEM model.

## 7.2 CBI limits on Ka-band RRLs

The brightest carbon RRLs expected in the 10 CBI channels are C57 $\alpha$  to C62 $\alpha$ . Four 1 GHz wide channels, centred at 27.5, 30.5, 33.5 and 35.5, are free from  $\alpha$  RRLs. Yet the CBI flux densities in each channel, inferred by cross-correlation with a processed IRAC 8  $\mu\text{m}$  template, are scattered about a single power law; no decrement is seen in the four channels devoid of RRLs. A  $1\sigma$  upper limit to the contribution of RRLs in a single channel is given by the rms dispersion about the best-fitting power law, of  $\sigma_{\text{RRL}} = 0.04 \text{ Jy}$ .

The expected RRL flux in the CBI channels is quite close to the above upper limit. In the C II region model of Section 6, the flux density from C62 $\alpha$ , at 26.95 GHz, in the 1 GHz wide CBI channel centred on 26.5 GHz, is 0.6 Jy under local thermodynamic equilibrium (LTE) conditions. However, for  $n < 100$  the excited energy levels leading to the emission of  $\alpha$  photons are severely depopulated relative to LTE at  $\sim 150 \text{ K}$  (Salem & Brocklehurst 1979; Walmsley & Watson 1982).<sup>12</sup> The exact level population in  $n = 62$  is very sensitive on temperature and dielectronic recombination. The value given by Walmsley & Watson (1982, their fig. 3) is  $b = 0.5$ , relative to LTE, implying a C62 $\alpha$  contribution of 0.3 Jy, which should be detectable by the CBI.<sup>13</sup> Lowering  $T_e$  to 50 K brings the predicted RRL flux down to  $3\sigma_{\text{RRL}}$ , i.e. marginally consistent with the CBI upper limit.

## 7.3 Mopra limits on K- and W-band RRLs

The detection of the RRL system of  $\rho$  Oph W in the C I model of Section 6.3 would be very difficult. The ensemble of clumps is optically thick below  $\sim 10 \text{ GHz}$ . At higher frequencies, the excited energy levels leading to the emission of  $\alpha$  photons are severely depopulated relative to LTE (Salem & Brocklehurst 1979; Walmsley & Watson 1982).

We none the less attempted to detect the RRL system of  $\rho$  Oph W using the UNSW-MOPS spectrometer (Section 3.3.2), and found no RRLs at the expected radial velocity,  $V_{\text{lsr}} = +3 \text{ km s}^{-1}$  (Brown & Knapp 1974; Pankonin & Walmsley 1978). With the line profiles observed at lower frequencies, of  $1.5 \text{ km s}^{-1}$  FWHM, we can estimate the expected contribution of RRLs in the Mopra data cubes and place upper limits on the high-frequency RRLs.

The ensemble of C II clumps subtends a solid angle of less than  $\Omega_c = \pi 1.5^2 \text{ arcmin}^2$ . If there are  $N_c = 30$  clumps spread uniformly over  $20 \times 20 \text{ arcmin}^2$ , then only one clump is expected on average in each 5 arcmin pixel. The expected intensity from one clump, covering about  $\pi 8^2 \text{ arcsec}^2$  is diluted in  $5 \times 5 \text{ arcmin}^2$ . At  $T_e = 150 \text{ K}$ , the emergent peak LTE intensity in C73 $\alpha$  from one clump is  $1262 \text{ MJy sr}^{-1}$ , or  $2.97 \text{ MJy sr}^{-1}$  when diluted in the 5 arcmin pixels. In dense and cold gas dielectronic recombination enhances the LTE departure coefficients to  $b \sim 1$ . Thus with a  $3\sigma$  upper

limit of  $1.1 \text{ MJy sr}^{-1}$  on C73 $\alpha$ , the Mopra data rule out ‘warm’ temperatures (note that collisionally excited lines, such as [C II] 158  $\mu\text{m}$ , are biased towards higher temperatures). By contrast, at  $T_e = 20 \text{ K}$ , the peak LTE RRL intensity in 5 arcmin pixels is  $0.38 \text{ MJy sr}^{-1}$ , and  $b \sim 0.3$ , so that the expected C73 $\alpha$  intensity is only  $0.12 \text{ MJy sr}^{-1}$  – consistent with its non-detection.

In the W band, the  $b$  coefficients are vanishingly small at 20 K temperatures. For C42 $\alpha$  and  $T_e = 20 \text{ K}$ , we approximate to the  $n = 50$  case of Salem & Brocklehurst (1979) [for  $\log(N_e/1 \text{ cm}^{-3}) = 2.5$  and with a 100 K background]:  $b = 5 \times 10^{-4}$ . The expected C42 $\alpha$  intensity in the 5 arcmin pixels is  $b \times 9.6 \text{ MJy sr}^{-1}$ , while the rms noise is  $188 \text{ MJy sr}^{-1}$ .

## 8 DISCUSSION

The [C II]  $\lambda 158 \mu\text{m}$  image of  $\rho$  Oph A by Yui et al. (1993), with a 15 arcmin beam, shows that C<sup>+</sup> is present and that [C II]  $\lambda 158 \mu\text{m}$  shares a similar extent as the cm-wave continuum. It is remarkable that S1 is not coincident with a [C II]  $\lambda 158 \mu\text{m}$  peak. In this section, we discuss the likely emission levels of C I continuum in the  $\rho$  Oph environment, and consider the possibility of combining both C I and spinning dust.

### 8.1 Exciting stars

#### 8.1.1 HD 147889

Atmospheric parameters for the two components of HD 147889 were obtained by fitting ‘Tlusty’ non-LTE model atmospheres (Lanz & Hubeny 2007) to the FEROS spectra (Section 3.3.1), with rotation velocities  $v \sin i$  of 50 and  $30 \text{ km s}^{-1}$  respectively, and a surface area ratio of 1.3. The temperatures are 23 000 and 20 000 K and the surface gravity  $\log(g)$  is 4.25 for both components [ $\log(g) < 4.0$  or  $> 4.5$  are ruled out]. The surface gravity is determined mainly from the strength of the line wings of H $\gamma$   $\lambda 4340$ . However, this strength also depends on the temperature. The temperature mainly comes from the strength of He I  $\lambda 4387$  and  $\lambda 4471$  as compared with Mg II  $\lambda 4481$  and the Si III triplet  $\lambda\lambda 4552, 4567, 4573$ .

The heliocentric velocities of each component were  $+64, -99 \text{ km s}^{-1}$  on UTC = 2006 February 07,  $-52 \text{ km s}^{-1}, +53 \text{ km s}^{-1}$  on UTC = 2008 May 16 and  $-39 \text{ km s}^{-1}$  and  $+33 \text{ km s}^{-1}$  on UTC = 2008 May 17. This gives us a systemic heliocentric velocity of  $-7 \text{ km s}^{-1}$ , or a local standard of rest velocity of  $+3 \text{ km s}^{-1}$  (so equal to that of the carbon RRLs), and a mass ratio of 1.3.

If the two components of HD 147889 are on the main sequence, as indicated by their surface gravities, then the stellar radii and masses can be inferred by interpolating the zero-age main-sequence models of Schaller et al. (1992). We obtain radii of 3.52 and  $3.10 R_\odot$ , and masses of 8.31 and  $6.36 M_\odot$ . But it must be borne in mind that the IR excess of HD 147889 and its interaction with the  $\rho$  Oph star-forming cloud make it a likely pre-main-sequence star, in the sense that it is still contracting towards the zero-age main sequence. The models of Behrend & Maeder (2001, their table 1) show that at an age of  $2.4 \times 10^5 \text{ yr}$  (so close to  $10^6 \text{ yr}$ , the approximate lifetime of dark clouds), a  $12 M_\odot$  star would still be contracting, with a surface temperature of 22 000 K and a radius of  $10.3 R_\odot$ . To make headway the spectral types we adopt are B2IV and B3IV, but we note that we lack a precise measurement of the stellar luminosities.

The line of sight to HD 147889 appears to be strongly affected by extinction from LDN 1688. The H-nucleus column density map reported in Section 5.1 gives  $N_H = 1.13 \times 10^{22} \text{ cm}^{-2}$  in the direction of HD 147889, or  $A_V = 6.76$  using the conversion factors

<sup>12</sup> We have cross-checked our calculations against those in Pankonin & Walmsley (1978) and equation (3) in Heiles et al. (1996).

<sup>13</sup> We have neglected the effects of stimulated emission, accounted for in the  $\beta$  coefficient of (Walmsley & Watson 1982, their fig. 5), because  $\beta \approx 1$  for the transitions considered here.

from Draine (2003) with  $R_V = 3.1$ . The  $A_V$  map from Ridge et al. (2006) gives  $A_V = 8.1$  at the position of HD 147889. However, a comparison between the observed  $B - V$  colour and that expected from the model atmospheres from Castelli & Kurucz (2003) gives  $E(B - V) = 0.8$  (or  $A_V \sim 2.5$ ). Yet the stellar radii inferred above require extinction values  $A_V = 4.5$  to be compatible with the photometry. Hence, the extinction towards HD 147889 is manifestly very structured on small scales, and requires an exceptionally large  $R_V = 5.6$  or higher if HD 147889 is still contracting.

### 8.1.2 S1 and SR3

S1 is a close binary system composed of a B4V star (Lada & Wilking 1988) and a K-type companion with a 10 mJy peak at 10 GHz (including its 2 mJy radio halo, André et al. 1988). For S1,  $T_{\text{eff}} \sim 15\,800$  K, and surface gravity  $\log(g/\text{cm s}^{-2}) = 4.0$ . The spectral type we adopt for SR3 is B6V (Elias 1978), or  $T_{\text{eff}} \sim 14\,000$  K,  $\log(g/\text{cm s}^{-2}) = 4.0$ . Lada & Wilking (1988, their section IIIb) and Bontemps et al. (2001) give bolometric luminosities  $L_\star$  for S1 and SR3. For S1,  $L_\star = 1100 L_\odot$ , which is consistent with B4V, but for SR3,  $L_\star = 100 L_\odot$ , which is too low for B6V. The spectral type of SR3 is probably closer to B9V.

## 8.2 Physical conditions

The 1.1 mm continuum data in Young et al. (2006) are strongly high-pass filtered and trace the smaller angular scales. They find an average density of  $\sim 10^6 \text{ cm}^{-3}$  in 44 molecular cores containing  $\sim 80 M_\odot$ , or about 1/20–1/100 the mass of the entire  $\rho$  Oph complex (see Section 5.1).

A density of  $n_H = 10^4$ – $10^5$  is given by Liseau et al. (1999) from PDR models of the far-IR line ratios. They fit [O I] 63, 145  $\mu\text{m}$ , while the [C II] 158  $\mu\text{m}$  levels can only be reproduced with  $n_H = 10^6 \text{ cm}^{-3}$  and an unrealistically low field  $G_0$ . Higher densities than  $10^6 \text{ cm}^{-3}$  are required to accommodate  $G_0 \sim 100$  inferred by Liseau et al. (1999). They treated HD 147889 as a main-sequence star, and used a distance of 150 pc. With the *Hipparcos* distance to HD 147889 of 135 pc and luminosity class IV we obtain  $G_0 = 629$ , using the model atmospheres from Castelli & Kurucz (2003).

Bypassing the PDR models, we can infer a H-nucleus density from the [C II] 158  $\mu\text{m}$  cooling rate (e.g. Tielens 2005, his equation (2.67)). The fluxes from Liseau et al. (1999) then give  $n_H \sim 3 \times 10^4$ – $2 \times 10^6 \text{ cm}^{-3}$  for temperatures of 10–100 K and a filling factor of  $f = 10^{-3}$ . Note, however, that the critical density of [C II] 158  $\mu\text{m}$  is  $2.7 \times 10^3 \text{ cm}^{-3}$  at 100 K, so that it does not trace the dense clumps required by the C I continuum model.

## 8.3 C I Strömgren spheres

The model atmospheres from Castelli & Kurucz (2003) predict that the C-ionizing luminosity of HD 147889 is  $\sim 25$  times that of S1 and 612 times that of SR3. From its vantage point at the back of the  $\rho$  Oph main cloud, HD 147889 illuminates the entire cloud (Liseau et al. 1999). By contrast, S1 is surrounded by its disc-like circumstellar nebula (which probably stems from the clumpy walls of a wind-blown cavity, see Section 5.1). Since S1 is optically visible, a fraction of its UV luminosity escapes. The small part of its carbon-ionizing flux that is absorbed in the dense circumstellar disc radiates a meagre 2 mJy at 5 GHz (André et al. 1988).

If the C II regions of  $\rho$  Oph are ionization-bounded nebulae their average electron density is given by ionization balance:  $n_e^2 = S/\alpha V$ ,

where  $V$  is nebular volume and  $S$  is the stellar luminosity in C-ionizing photons (below H-ionizing energies). We use the total recombination coefficients  $\alpha$  from Nahar & Pradhan (1997), assuming  $T_e = 100$  K. For optically thin radiation, the total C II region flux density is

$$F_\nu = S B_\nu \kappa_\nu^{-1} / \alpha, \quad (1)$$

where  $B_\nu$  is the Planck function and  $\kappa_\nu^{-1}$  is the C I free-free opacity for unit electron density.

For S1, we obtain  $S = 9.9 \times 10^{45} \text{ s}^{-1}$ , which for a closed geometry should give an integrated flux density of 458 mJy at 31 GHz. S1 is not detected in the CBI maps. In Section 5.3, we report a 31 GHz point-source flux density of  $1.3^{+7}_{-4}$  mJy for S1. It appears that the circumstellar nebula around S1 must be disc-like, or else sufficiently clumpy that  $\sim 90$  per cent of C-ionizing photons escape the nebula. This is consistent with the fact that S1 is an optically visible star (by contrast with SR3).

For SR3, we have  $S = 4.1 \times 10^{44} \text{ s}^{-1}$ . The predicted flux density in a closed geometry is 20 mJy at 31 GHz, consistent with its non-detection by the CBI (the 31 GHz point-source flux density of SR3 is  $2.0^{+7}_{-3}$  mJy).

If HD 147889 has settled on the main sequence, we find  $S = 1.4 \times 10^{47} \text{ s}^{-1}$ , and an upper limit for the 33 GHz flux density of 6.5 Jy. The background-subtracted 33 GHz flux density inside the CBI PB aperture of 45 arcmin is 6.7 Jy, of which  $\sim 1.5$  Jy stem from the diffuse H II region surrounding HD 147889. This is close to the levels required for an ionization bounded and spherical nebula. But part of the C-ionizing radiation should escape the nebula. Thus for the C I continuum interpretation, it is necessary that HD 147889 be a pre-main-sequence binary star that is still contracting, with a primary stellar radius of about  $4.5 R_\odot$ , and a mass of  $\sim 10 M_\odot$ , so that  $\log(g) \sim 4$  to 4.5 (as inferred from the FEROS spectroscopy), and a secondary mass of  $7.7 M_\odot$ .

The C II Stromgren sphere around HD 147889 extends out to  $\sim 10$  arcmin, the projected distance to  $\rho$  Oph W. For a filled sphere, the required electron density is  $\sim 100 \text{ cm}^{-3}$ , implying H-nucleus densities of  $\sim 10^6 \text{ cm}^{-3}$ . Such a C II region would be optically thin at 5 GHz and reach  $\sim 10$  Jy, which is ruled out by the data. Thus, the C II region around HD 147889 must be a thin shell, as indicated by the geometry of  $\rho$  Oph W. However, in order to reach the densities required by the SED model of Fig. 6, the thickness of the  $\rho$  Oph W C II region should be only 2–3 arcsec, which is surprisingly thin. Such a thin shell could be replaced by an ensemble of flat clumps seen edge-on (see Section 6.3).

We have modelled the C II regions in  $\rho$  Oph using the CLOUDY photoionization package (version c07.02.01, last described by Ferland et al. 1998). We treat  $\rho$  Oph W as a shell in an open geometry, separated from HD 147889 by its projected distance, while S1 and SR3 are embedded in ionization-bounded circumstellar nebulae, with a fiducial inner radius of  $10^{15} \text{ cm}$ . The predicted C II layer in  $\rho$  Oph W is extremely narrow, with a width  $\delta < 1.2$  arcsec at densities  $> 10^6 \text{ cm}^{-3}$ , which is consistent with the thin ridge model. The solid angle subtended by the C II region in  $\rho$  Oph W, which consists of an ensemble of  $N_c = 30$  sheets, each 3.7 arcmin long, is about  $30 \times 3.7 \times \delta / 60 \text{ arcmin}^2$ . This is a factor of  $\sim 100$  larger than in the C II regions around S1 and SR3 (if the H-nucleus density is constant at  $10^6 \text{ cm}^{-3}$ ).

## 8.4 Origin of the 2MASS diffuse emission

The 2MASS  $K_s$  band emission from  $\rho$  Oph W is coincident with the 31 GHz ridge. What is the nature of the nebosity seen in

the 2MASS  $J$ ,  $H$  and  $K_s$  images? All three 2MASS bands share a similar morphology with the IRAC images, although not exactly coincident.

#### 8.4.1 Problems with near-IR scattered light, VSG continuum and free-free

We estimated that the diffuse intensities in  $\rho$  Oph W drop at shorter wavelengths, in ratios  $J : H : K \sim 1 : 2.2 : 2.7$ .<sup>14</sup> This is at odds with the colours expected from scattered light. Padoan, Juvela & Pelkonen (2006) calculate that the emergent intensities of scattered light in neutral clouds should increase by a factor of 4 from  $K$  to  $J$ . These ratios are unlikely to be affected by extinction. The interstellar extinction towards  $\rho$  Oph, excluding intranebulary extinction, can be estimated from the value of the colour excess  $E(B - V)$  in the maps of Schlegel et al. (1998). Near  $\rho$  Oph but outside any dust clouds extinction is very low,  $A_V < 0.1$ , as expected for Gould belt clouds, which raises the  $J$ -band intensities by a meagre 3 per cent.

On the other hand, even at 150 K the  $C_1$  continuum is cut-off by its Wien tail above  $\sim 5\mu\text{m}$ , and is  $\sim 30$  times fainter than the  $8\mu\text{m}$  nebosity seen in the IRAC 4 image at  $8\mu\text{m}$ . It is unlikely that the 2MASS images trace a 1000 K  $C^+$  plasma because the solid angle of  $\rho$  Oph W in the  $K$ -band image is about 5 arcmin<sup>2</sup>, which would give an optically thick continuum of  $\sim 10^4$  Jy at 5 GHz.<sup>15</sup>

Is it possible that the near-IR continuum stems from a VSG population sharing a similar morphology as the PAHs that emit in the IRAC bands? We note that the circumstellar nebulae around S1 and SR3 are also seen in the 2MASS  $K_s$ -band images, with  $JHK$  colours as for  $\rho$  Oph W and discrepant from that of scattered light. Sublimation dust temperatures of  $\sim 1000$  K are required to explain the S1 and SR3 nebulae in terms of large dust grains. So, it is likely that the same VSGs that would account for the  $\rho$  Oph W near-IR emission would also be found in S1 and SR3. We return to the discussion on spinning dust in Section 5.3.

#### 8.4.2 Rovibrational $H_2$

An interesting alternative to the VSG continuum is the possibility that the  $J$ ,  $H$  and  $K$ -band emission in  $\rho$  Oph W stems from  $H_2$  rovibrational lines. Habart et al. (2003, their fig. 2) present a (1-0)S(1)  $H_2$  image, in which it may be appreciated that  $\rho$  Oph W is slightly offset by  $\sim 10$ – $20$  arcsec to the south-east compared to the ISOCAM PAH emission in the LW2 filter (5– $8.5\mu\text{m}$ ). There is also a hint of a shift in Fig. 5 between 2MASS  $K_s$  band and IRAC  $8\mu\text{m}$ , which may be explained if 2MASS  $K_s$  is mostly due to rovibrational  $H_2$  and IRAC  $8\mu\text{m}$  to PAHs. Here, we use the *Spitzer* spectroscopy to further investigate relationships between  $H_2$ , PAHs and 31 GHz.

The IRS data on  $\rho$  Oph W allow estimating the intensity of the pure rotational lines  $H_2$  S(1) and S(2), in the same manner as used in Section 5.3 for the PAH 11.3  $\mu\text{m}$  band. Table 3 lists the  $H_2$  line fluxes in the spectra we analysed. They are consistent with table 1 of Habart et al. (2003).

A tentative correlation between the  $H_2$  fluxes and 31 GHz intensities can be inferred from a comparison between Table 3 and Table 2. Note that in the specific case of SR3, the 31 GHz intensity

**Table 3.** *Spitzer* IRS  $H_2$  line intensities in  $\text{W m}^{-2} \text{sr}^{-1}$ .

|                | $\rho$ Oph W          | SR3      | S1        | S1off     |
|----------------|-----------------------|----------|-----------|-----------|
| $H_2(0-0)S(1)$ | 3.66(−7) <sup>a</sup> | 1.55(−7) |           |           |
| $H_2(0-0)S(2)$ | 2.94(−7)              | 1.86(−7) | <1.02(−8) | <2.75(−9) |

<sup>a</sup>The power of 10 exponent is indicated in parentheses.

towards SR3 should be  $1.4 \pm 0.2(−1)$ , as measured in the 31 GHz image, and not as tabulated in Table 2 (where we are testing for 31 GHz counterparts to the mid-IR compact source around SR3).  $H_2$  is weak or undetected in the positions of low 31 GHz intensities (i.e. S1 and S1off), despite the coincidence with the peak mid- and far-IR intensities, while  $H_2$  is bright at the 31 GHz peak (i.e. on  $\rho$  Oph W) and in SR3. The  $H_2$  lines are undetected towards S1. The values reported in Table 3 for S1 and S1off are upper limits derived from formally extracting the  $H_2$  line flux, despite the absence of visible lines.

In the molecular layers of PDRs, the C-ionizing UV radiation also excites the electronic states of  $H_2$ , which then decay in a rovibrational cascade leading to the observed near-IR fluorescent lines. The conditions in  $\rho$  Oph W are very similar to those found in NGC 2023. Black & van Dishoeck (1987) reproduce the near-IR  $H_2$  line system of NGC 2023 with an incident UV specific intensity field of  $I_{UV} = 1240$  in units of the 1000 Å UV background at the solar neighbourhood. For  $\rho$  Oph W, we find that  $I_{UV} = 545$ , if HD 147889 is on the main sequence, or higher if it is still contracting. The more recent models of Habart et al. (2003) demonstrate that the near-IR  $H_2$  lines in  $\rho$  Oph W are fluorescent.

Therefore in the  $C_1$  model, we expect that the 31 GHz continuum be coincident with fluorescent  $H_2$ . The 2MASS-CBI match in  $\rho$  Oph W could then be explained if the 2MASS filters are dominated by  $H_2$  line emission.

Given the  $H_2(1-0)S(1)$  intensity map of Habart et al. (2003), we estimate that ro-vibrational  $H_2$  accounts for all of the diffuse 2MASS  $K_s$  flux seen in  $\rho$  Oph W.  $H_2(1-0)S(1)$ , on its own, accounts for 20 per cent of the 2MASS  $K_s$ -band specific intensities. The exact contribution is difficult to estimate because the diffuse nebosity in 2MASS is at a very low level. The noise in 2MASS  $K_s$  is  $0.35 \text{ MJy sr}^{-1}$ , while the peak intensities above background in  $\rho$  Oph W are  $\sim 1 \text{ MJy sr}^{-1}$ . The  $H_2(1-0)S(1)$  line, if diluted in the  $K_s$  filter, corresponds to intensities of  $0.2 \text{ MJy sr}^{-1}$  (using the  $H_2(1-0)S(1)$  image in Habart et al. 2003, their fig. 2). Table 3 from Black & van Dishoeck (1987) allows to estimate that  $H_2(1-0)S(1)$  represents 21.8 per cent of the total  $H_2$  contribution in the 2MASS  $K_s$  filter. Therefore,  $H_2$  ro-vibrational emission can account for the entire 2MASS  $K_s$ -band flux.

### 8.5 Both $C_1$ and spinning dust?

This work focuses on the 31 GHz continuum as seen by the CBI. Yet inspection of the *WMAP* Ka map reveals that the entire  $\rho$  Oph cloud is outlined at 33 GHz, albeit at  $\sim 1/3$  the intensities in  $\rho$  Oph W. In particular, the eastern filamentary extensions of  $\rho$  Oph, LDN 1729 and LDN 1712, at  $0.03 \text{ MJy sr}^{-1}$  and  $0.016 \text{ MJy sr}^{-1}$ , are not detected in the 2.3 GHz map of Baart et al. (1980, in which no region of  $\rho$  Oph has a counterpart). The diffuse emission surrounding our 45 arcmin centred on  $\rho$  Oph W also appears to have a positive spectral index between 2.3 and 33 GHz  $\alpha_{2.3}^{33}$ . If we correct for a diffuse background at  $0.03 \text{ MJy sr}^{-1}$ , the *WMAP* 33 GHz flux density inside the CBI PB aperture drops from 14 to  $\sim 9$  Jy.

<sup>14</sup> We used the zero-points for the Montage mosaics, took the median intensity values in a square box 20 pixels on a side, centred on J2000 16:25:57.88–24:21:11.7, and subtracted a median background extracted from a similar box but centred on J2000 16:25:58.10–24:14:42.4.

<sup>15</sup> Note, however, that the faint continuum from the diffuse H II region about HD 147889 is at  $\sim 7000$  K and present in the  $K$  band.

C I can better accommodate a reduced 33 GHz flux density, since the 2.3–33 GHz rise is shallower ( $\alpha_{2.3}^{33}$  drops from 0.69 to 0.52). But what is the origin of the background? The first possibility that springs to mind is spinning dust, which does not require an ionization source, and scales linearly with density. We could also envision an ensemble of C I-emitting dense clumps illuminated by the general interstellar UV field. In this case, the specific intensity in the optically thin regime at 33 GHz can be written:

$$I_\nu = f L n_{\text{C}^+} n_e B_\nu \kappa_\nu^1, \quad (2)$$

where  $L$  is the depth of the  $\rho$  Oph cloud,  $f$  is the filling factor and  $\kappa_\nu^1$  is as in equation (1). An upper limit to the product  $n_{\text{C}^+} n_e$  can be obtained by ionization balance in ionization-bounded clumps

$$A l n_{\text{C}^+} n_e \alpha < s_{\text{C}} A, \quad (3)$$

for clumps with depth  $l$  and area  $A$ , where

$$s_{\text{C}} = \int_{\lambda_{\text{C}}}^{\lambda_{\text{H}}} d\lambda \lambda \pi J_\lambda / (hc) \quad (4)$$

is the flux of C-ionizing photons per unit area in the interstellar radiation field  $J_\lambda$ . If  $fL \approx l$ , the depth of a single clump, then we have an upper limit to any C I continuum diffuse background intensity

$$I_\nu^u = B_\nu \kappa_\nu^1 s_{\text{C}} / \alpha. \quad (5)$$

The interstellar radiation field of Mathis et al. (1983) gives  $I_\nu^u = 0.4 \text{ MJy sr}^{-1}$ , which is satisfyingly a factor of 4 above the observed values in  $\rho$  Oph. As in the case of  $\rho$  Oph W (Section 6), we require beam-diluted optically thick clumps covering a solid angle of  $\sim \Omega_{\text{beam}} T_{\text{rms}} / T_e$ . Thus to explain the absence of  $\rho$  Oph in Baart et al. (1980) with a noise of  $\sim 30 \text{ mK}$  and a beam of 20 arcmin FWHM, the projected linear size of the clump ensemble should be  $< 1 \text{ arcmin}$ , if  $T_e \sim 100 \text{ K}$ . In  $\rho$  Oph W such narrow dimensions could perhaps be interpreted as a very narrow C II shell around HD 147889. But for the diffuse emission such a geometry seems very contrived.

## 9 CONCLUSION

We have found that the well studied and nearby molecular cloud  $\rho$  Oph is surprisingly bright at 31 GHz, or  $\sim 1 \text{ cm}$  wavelengths. The most conspicuous feature revealed by the CBI data is the  $\rho$  Oph W PDR.

Comparison with *WMAP* images shows that the cm-emission is not the Rayleigh-Jeans tail of the sub-mm emitting dust. Bulk dust properties are inferred from new *ISO*-LWS parallel mode data. Archival *Spitzer* data allow quantifying PAH emission. None of the comparison images matches the CBI data, except for IRAC 8  $\mu\text{m}$  and 2MASS  $K_s$ , which closely follow the 31 GHz ridge along  $\rho$  Oph W. *Spitzer* IRS spectroscopy in four apertures hint at a possible correlation between 31 GHz intensity and the  $\text{H}_2$  pure-rotational lines: the  $\text{H}_2$  lines are detected only where 31 GHz intensities are bright (i.e. towards SR3 and  $\rho$  Oph W, and not in the vicinity of S1).

We considered several interpretations for the 31 GHz emission, requiring either an additional radio continuum component such as magnetic or spinning dust, or unexpected physical conditions, such as in a very dense and cold plasma. We find that both spinning dust and C I continuum can explain the data.

(i) Magnetic dust is discarded on morphological grounds. The expected 31 GHz intensity from a magnetic enhancement of the

grain opacity is at odds with the CBI data. The polarization levels required by magnetic dust are not observed.

(ii) Spinning dust can account for the radio spectrum. But the predicted levels in S1 are in excess by a factor of  $> 40$  at  $3\sigma$ . We take the intensities in PAH 11.3  $\mu\text{m}$  as a proxy for the mid-IR VSG emission, which is approximately proportional to both the VSG column and local UV intensity  $U$ . Taking into account the range of spinning dust emissivities in all possible environments, the uncertainties in our 31 GHz map can marginally reconcile spinning dust with the data (i.e. at  $3\sigma$  variations).

(iii) Alternatively, a cold plasma such as that found in C II regions could explain the 31 GHz emission. The star HD 147889, a binary pre-main-sequence star with spectral types B2IV, B3IV, emits sufficient C-ionizing UV radiation to interpret  $\rho$  Oph W as a C II region. But the absence of detectable  $< 10 \text{ GHz}$  signal requires optically thick emission, and hence high H-nucleus densities ( $n_{\text{H}} \sim 10^7 \text{ cm}^{-3}$ , almost a factor of 10 higher than inferred in the literature), implying a hitherto unobserved molecular phase of the ISM. In  $\rho$  Oph, this molecular phase takes the form of an ensemble of dense clumps or sheets at temperatures of the order of 50 K or less. The cold plasma interpretation explains the 2MASS–CBI correlation through an important fluorescent  $\text{H}_2$  contribution to the 2MASS bands.

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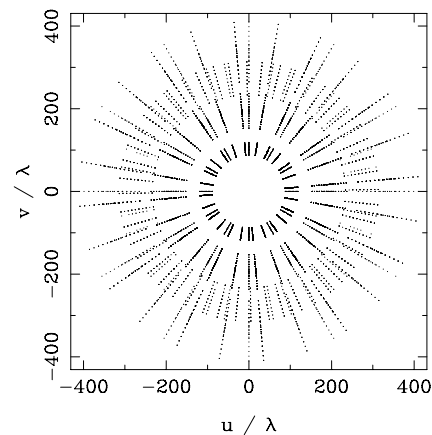
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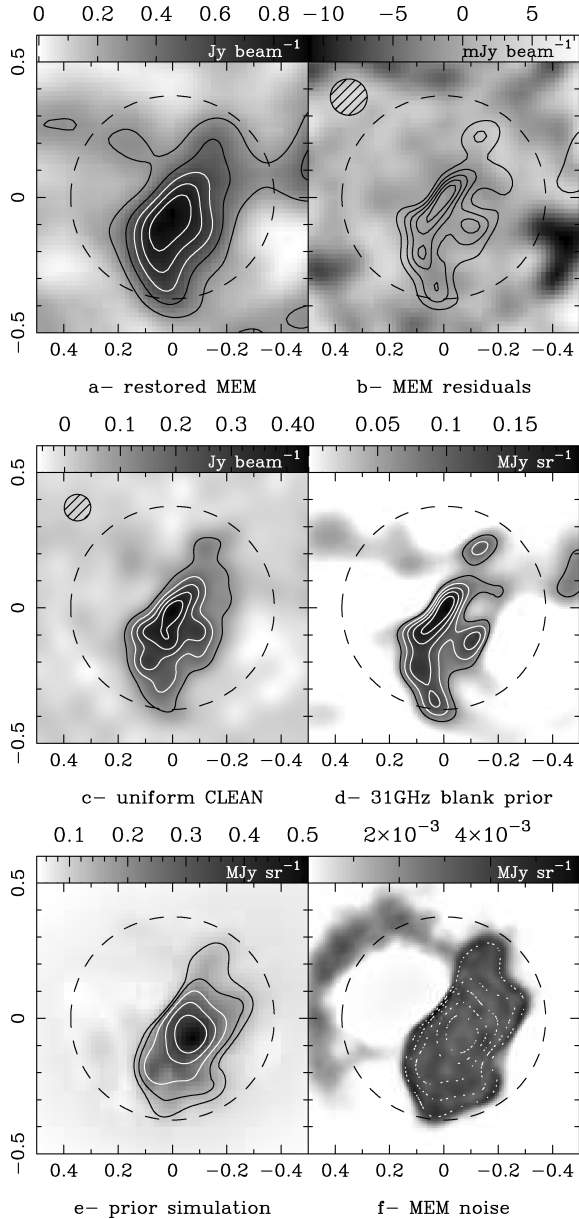
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## APPENDIX A: IMAGE RECONSTRUCTION

Image reconstruction from interferometer data is an instance of the inverse problem. The compact configuration of the CBI interferometer results in the  $(u, v)$  coverage shown in Fig. A1. Missing spacing and noise imposes non-linear deconvolution methods. With a uniform grid, the number of free parameters (here  $256^2$ ) can exceed the number of independent data points, so that the fit is degenerate. In this case, we take as a measure of the quality of fit  $\chi^2/f$ , where  $f$  is the number of independent data points.  $\chi^2/f$  should be close to 1 for a satisfactory model. The first few conjugate gradient iterations in the least-squares algorithm fit the bulk of the signal, but inevitably converge on noisy models, with  $\chi^2/f$  values much less than 1. MEM regularization prevents the models from fitting the noise. The model shown in Fig. 1 has  $\chi^2/f = 1.20$ , which is somewhat high, but reconcilable with 1.0 through a 10 per cent increase in the noise. The noise in each visibility point is calculated as the



**Figure A1.**  $(u, v)$  coverage of the CBI in the compact configuration used for the observations of  $\rho$  Oph W.



**Figure A2.** MEM restored image and comparison reconstructions. The axes and dashed circle follow from Fig. 1. (a) Restored image, with contour levels at 0.012, 0.286, 0.446, 0.581, 0.702 and 0.813 Jy beam<sup>-1</sup>, and peak at 0.916 Jy beam<sup>-1</sup>. (b) MEM contours overlaid on the residual image. The natural-weight synthetic beam is indicated by the hatched ellipse. (c) DIFMAP CLEAN reconstruction of the CBI data, in uniform weights. Contour levels are 0.098, 0.185, 0.257, 0.323 and 0.382 Jy beam<sup>-1</sup>. (d) A CBI MEM model with a blank prior is shown in grey-scale, with contours at 0.06, 0.09, 0.12, 0.15 and 0.17 MJy sr<sup>-1</sup>. (e) Average MEM model of CBI simulations on the prior image used to produce our best model. Contours are at 0.098, 0.185, 0.257, 0.323 and 0.382 MJy sr<sup>-1</sup>, overlaid on a grey-scale of the input image. (f) Averaged MEM contours overlaid on the rms dispersion of the MEM models.

rms scatter of  $\sim 120$  samples, and does not include residual errors in calibration, which may perhaps amount to 10 per cent.

A reconstruction starting from a blank image as initial condition, rather than the image prior  $M_i$ , converges on essentially the same model as Fig. 1, but with a higher  $\chi^2/f = 1.4$ , and thus larger residuals. The prior we chose accounts for some of the extended emission seen by *WMAP*, but keeps the IRAC resolution by replacing the emission within the CBI PB with the IRAC 8  $\mu$ m image, suitably scaled and processed so as to resemble the blank-prior MEM models (i.e. we patched-out stellar features, namely S1 and SR3, see below). This patched image was then fed as initial condition and prior into a sky-plane MEM deconvolution of the *WMAP* Ka image, producing the prior image used for the CBI reconstructions in Fig. 1, with  $\chi^2/f = 1.2$ .

The CBI observations and the quality of the MEM model can be examined through the restored image and the residuals shown on Figs A2(a) and (b). The residual image is the dirty map (produced with the DIFMAP package using natural weights, Shepherd 1997), of the residual visibilities (the difference between the observed and model visibilities). The restored image is the sum of the residual image, after division by the CBI PB, and the MEM model convolved with an elliptical Gaussian fit to the natural-weight synthetic beam ( $8.17 \times 7.99$  arcmin<sup>2</sup>). In natural weights, the theoretical rms noise of the dirty map is 3.4 mJy beam<sup>-1</sup>. The dynamic range of the restored image shown in Fig. A2 is of the order of 100.

We examined the statistical properties of the MEM reconstructions with the simulations described in appendix B of Casassus et al. (2006). These simulations are relevant to assess the effects of the CBI beam on the morphological analysis of Section 4.1, and to estimate the dynamic range of the MEM reconstructions. The CBI MEM prior is a suitable template. We ran the same MEM algorithm as applied to the CBI visibilities on a simulation of CBI observations on the prior used for the reconstruction of Fig. 1. Fig. A2 compares this prior image with the average and dispersion of the MEM models run on 90 realizations of complex visibility noise. Note that in this case we used a blank prior with  $\lambda = 20$  and  $M_i = 0.3$  Jy sr<sup>-1</sup>. The 31 GHz model image obtained with this MEM reconstruction is shown in Fig. A2(d). It is very similar to Fig. 1. We take this similarity as a proof of robustness of the MEM reconstructions, and also as ground to extrapolate the dynamic range of the simulations, of  $\sim 20$ , to the CBI images.

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